



(51) International Patent Classification:

H01J 37/32 (2006.01) H02M 5/275 (2006.01)
H02M 5/22 (2006.01) H02M 5/293 (2006.01)
H02M 5/257 (2006.01) H02M 5/297 (2006.01)
H02M 5/27 (2006.01)

(21) International Application Number:

PCT/US2016/049017

(22) International Filing Date:

26 August 2016 (26.08.2016)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

14/843,412 2 September 2015 (02.09.2015) US

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(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG,
MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM,
PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC,
SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ,
TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU,
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,
DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,
SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,
GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— as to applicant's entitlement to apply for and be granted a
patent (Rule 4.17(ii))

Published:

— with international search report (Art. 21(3))

(54) Title: DIRECT THREE PHASE PARALLEL RESONANT INVERTER FOR REACTIVE GAS GENERATOR APPLICATIONS

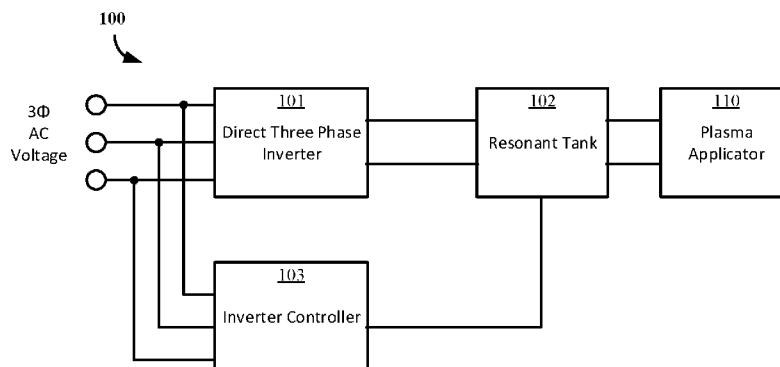


FIG. 1

(57) Abstract: A power system for a reactive gas generator (100) can include a direct three phase inverter (101). A resonant tank (102) can further be included to receive a square wave output of the direct three phase inverter and provide a sine wave output. The power system can include an inverter controller (103) that turns on and off selected switches of the direct three phase inverter based on states of the three phases of a three phase AC power supply, where a switch is turned on with an adaptive ON time and a modulated OFF time depending on a desired output power.

DIRECT THREE PHASE PARALLEL RESONANT INVERTER FOR REACTIVE GAS GENERATOR APPLICATIONS

BACKGROUND

[0001] Power supplies, particularly in the field of plasma applications, require high
5 frequency (e.g., 400 kHz to 4 MHz), high voltage (e.g., 1 kVpk to 10 kVpk), and high power (e.g.,
5 kW to 50 kW) capabilities.

[0002] In addition, power supplies for plasma applications, such as reactive gas
generators, must be able to react to the plasma's impedance changing characteristics so that the
power remains stable during system operation, perform efficiently, and be able to fit within the
10 ever decreasing physical area made available to the power supply. A power system for plasma
applications may involve converting the standard three phase 208VAC/480VAC, 50/60Hz supply
to a high frequency, varying (high) AC output voltage power supply.

BRIEF SUMMARY

[0003] Power systems suitable for high frequency applications are presented. The
15 described power systems involve direct three phase parallel resonant inverter schemes.

[0004] In some implementations, a power system includes a direct three phase inverter
and a resonant tank. The direct three phase inverter can have a first phase input line, a second
phase input line, and a third phase input line for receiving a three phase AC input. The resonant
tank can be coupled to the direct three phase inverter to receive an output of the direct three phase
20 inverter.

[0005] In some implementations, a power system includes a direct three phase inverter
and an inverter controller. The direct three phase inverter can have a first phase input line, a second
phase input line, and a third phase input line for receiving a three phase AC input. The inverter
controller can also be connected to the first phase input line, the second phase input line, and the
25 third phase input line for receiving the three phase AC input. The inverter controller controls the
direct three phase inverter based on states of the three phases of the three phase AC input.

[0006] In some implementations, a power system includes a direct three phase inverter, a
resonant tank, and an inverter controller. The direct three phase inverter can have a first phase
input line, a second phase input line, and a third phase input line for receiving a three phase AC
30 input. The resonant tank can be coupled to the direct three phase inverter to receive an output of
the direct three phase inverter to generate a sine-wave output. The inverter controller can also be
connected to the first phase input line, the second phase input line, and the third phase input line
for receiving the three phase AC input. In addition, the inverter controller can be coupled to the
resonant tank to receive a sensed output power and sensed output current. The inverter controller

can supply control signals to the direct three phase inverter based on states of the three phases of the three phase AC input and the sensed output power and sensed output current.

[0007] A method of supplying power to a reactive gas generator can include providing a direct three phase inverter. The method can further include providing one or both of a resonant
5 tank for converting the square wave output of the direct three phase inverter to a sine wave and an inverter controller for controlling the switches of the direct three phase inverter.

[0008] The method can further include operating the direct three phase inverter by turning on and off selected switches based on states of the three phases of a three phase AC power supply, where a switch is turned on with an adaptive ON time and a modulated OFF time depending on
10 desired output power.

[0009] This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter.

15 BRIEF DESCRIPTION OF THE DRAWINGS

[0010] **Figure 1** is a simplified block diagram of a reactive gas generator system implementing an example power system.

[0011] **Figures 2A-2C** illustrate a variety of configurations for a power system.

[0012] **Figures 3A-3C** illustrate suitable resonant tanks that may form a part of various
20 power systems as described herein.

[0013] **Figure 4A** illustrates an example implementation of a direct three phase parallel resonant inverter power system.

[0014] **Figures 4B and 4C** illustrate example three phase AC source configurations that may be used with a direct three phase parallel resonant inverter power system.

25 [0015] **Figures 5A and 5B** illustrate examples of uni-directional switch configurations.

[0016] **Figure 6** is an example inverter power stage.

[0017] **Figure 7** illustrates an example inverter controller.

[0018] **Figure 8** illustrates an example implementation of an inverter controller.

[0019] **Figure 9** illustrates an example process carried out by an inverter controller.

30 [0020] **Figures 10A and 10B** illustrate adaptive ON time control.

[0021] **Figure 11A** illustrates a simplified control logic for basic driver operation.

[0022] **Figure 11B** provides a timing diagram representation for the basic driver operation of the simplified control logic of Figure 11A.

[0023] **Figure 12** provides a detailed snapshot of the simplified timing diagram of Figure

11B from t1 to t2.

[0024] **Figures 13A-13D** illustrate current flow and operation of an inverter in response to the gate driving logic operations shown in the simplified timing diagram of Figure 12.

[0025] **Figures 14A-14F** show a schematic of a plasma generating system with a direct
5 three phase parallel resonant inverter from which simulations were carried out.

[0026] **Figures 15A-15K** show plots of simulation results from the schematic of Figures 14A-14F for a full 15 kW output load.

[0027] **Figures 16A-16K** show plots of simulation results from the schematic of Figures 14A-14F for a 5 kW output load.

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DETAILED DISCLOSURE

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[0028] Power systems suitable for high frequency applications are presented. High frequency, high voltage, and high power applications can be supported by a power system with a direct three phase inverter. A robust and stable range of operation is further supported by the inclusion of a one-shot gate driving circuit and adaptive ON time control. The adaptive ON time control, using the one-shot gate driving circuit, provides a fairly constant output frequency and
adaptive ON time based on the components and load variation. This is how the direct three phase inverter achieves zero current switching for both turn ON and turn OFF.

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[0029] As used herein, “adaptive ON time” refers to an ON time that increases or decreases in length of time, when the frequency for the signal changes, so that the resulting ON time can be considered constant as the OFF time changes. In an example implementation, a frequency command signal can be used to modulate an OFF time while slightly increasing the ON time at light loads and modulate the OFF time while decreasing the ON time at heavier loads so that the ON time appears to remain constant as the OFF time changes.

25

[0030] Figure 1 is a block diagram of a reactive gas generator system implementing an example power system. The reactive gas generator system **100** includes a plasma applicator **110** that operates using a high frequency, high voltage signal applied to electrode and applicator transformer winding of the plasma applicator **110**. This signal can be generated from a standard three phase supply (e.g., 208VAC/480, 50/60Hz supply) by a direct three phase parallel resonant inverter scheme using a direct three phase inverter **101**, a resonant tank **102**, and an inverter controller **103**.
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[0031] The inverter **101** can be connected to each of the three phases of the three phase power supply via the three signal lines of the delta or wyes configuration of the supply. The inverter controller **103** turns on and off the switches of the inverter **101** while the three phase supply is input to the inverter **101** to transform the 50Hz or 60Hz signal to, for example, 400 kHz

to 4 MHz. The output of the inverter **101** drives the resonant tank, which converts the high frequency square wave from the inverter **101** to a sine wave signal for the plasma applicator **110**. The inverter controller **103** can receive feedback from the resonant tank **102** to adjust the control signal(s) for the inverter **101**.

5 [0032] Figures 2A-2C illustrate a variety of configurations for a power system. Referring to Figure 2A, a power system **200** according to an embodiment includes a direct three phase inverter **201**, a resonant tank **202**, and an inverter controller **203** co-located in a power system packaging. The configuration illustrated in Figure 2A can be suitable for use with plasma generators, for example as part of the reactive gas generator system **100**. The power system
10 packaging containing the power system **200** can be sized to appropriately fit within an available area in a plasma generator apparatus or a manufacturing center in which the plasma generator is deployed. In some cases, as illustrated in Figure 2B, a power system **210** can include a direct three phase inverter **211** and an inverter controller **213**. This component (the power system **210**) can be used in a variety of applications – with or without a resonant tank. When used for plasma
15 generation applications, a resonant tank **102** can be provided along with the power system **210** to form a power system suitable for use with plasma generators. Figure 2C illustrates yet another configuration of a power system. In Figure 2C, a power system **220** can include a direct three phase inverter **221** and a resonant tank **222**. A separate inverter controller **223** can be provided to appropriately turn on and off the switches of the direct three phase inverter **221**.

20 [0033] Figures 3A-3C illustrate suitable resonant tanks that may form a part of various power systems as described herein. For example, the resonant tank may be a parallel resonant tank such as shown in Figure 3A, a series resonant tank such as shown in Figure 3B, a series-parallel resonant tank such as shown in Figure 3C, or a combination thereof.

[0034] Figure 4A illustrates an example implementation of a direct three phase parallel resonant inverter power system. The system illustrated in Figure 4A can be used to implement the
25 direct three phase inverter **101**, resonant tank **102**, and inverter controller **103** of Figure 1 in any of the configurations shown in Figures 2A-2C. Figures 4B and 4C illustrate example three phase ac supply configurations that may be used with a direct three phase parallel resonant inverter power system.

30 [0035] Referring to Figure 4A, a direct three phase inverter **400** can include six switches **401**, **402**, **403**, **404**, **405**, and **406**. The six switches are uni-directional so that only one direction of current path is available when a switch is turned on. The switches **401**, **402**, **403**, **404**, **405**, and **406** can include, but are not limited to, transistors such as bipolar junction transistors (BJTs); insulated gate bipolar transistors (IGBTs); and field effect transistors (FETs), including MOSFETs

(metal oxide semiconductor field effect transistors) and high electron mobility transistors (HEMTs). In many cases a power device including, but not limited to, a power transistor of any of the above described transistors (e.g., of sizes and/or materials having appropriate breakdown voltages) is selected for as part of the switch.

5 [0036] Figures 5A and 5B illustrate examples of uni-directional switch configurations. As illustrated in Figure 5A, a switch for a direct three phase inverter can include a power device such as power transistor **500** and four diodes directing the current in a particular direction depending on the voltage across the various nodes. A control signal **C** is applied to turn on or off the transistor and the signal nodes **X** and **Y** couple the switch between a phase input and a resonant tank. In
10 another example as illustrated in Figure 5B, a switch for a direct three phase inverter can include two power transistors **510**, **511** that provide two directions for current to flow when the control signal **C** is applied with respect to **C'**. By eliminating the additional diodes, there is also no reverse recovery affecting efficiency.

[0037] Figure 6 illustrates an example inverter power stage. The example inverter power
15 stage has a direct three phase inverter with six switches implemented using the example uni-directional switch configuration of Figure 5A. According to the illustrated implementation (and indicated in Figure 4A), the first switch **401** is assigned as Q1, the second switch **402** is assigned as Q3, the third switch **403** is assigned as Q5, the fourth switch **404** is assigned as Q4, the fifth switch **405** is assigned as Q6, and the sixth switch **406** is assigned as Q2.

20 [0038] Referring to both Figure 4A and Figure 6, pairs of the switches are connected at one end to a phase input from a three phase power supply such as the example power supply configurations of wyes and delta respectively shown in Figures 4B and 4C. In this example switches **401** (Q1) and **404** (Q4) are connected to the first phase input A (voltage signal Va), switches **402** (Q3) and **405** (Q6) are connected to the second phase input B (voltage signal Vb),
25 and switches **403** (Q5) and **406** (Q6) are connected to the third phase input C (voltage signal Vc). The other ends of each of the switches are coupled to a resonant tank **408**.

[0039] As shown in Figure 4A, an inverter controller **410** provides the control signals to turn on and off each of the six switches **401**, **402**, **403**, **404**, **405**, and **406**. Here, a first output c1 is coupled to the first switch **401**, a second output c2 is coupled to the second switch **402**, a third
30 output c3 is coupled to the third switch **403**, a fourth output c4 is coupled to the fourth switch **404**, a fifth output c5 is coupled to the fifth switch **405**, and a sixth output c6 is coupled to the sixth switch **406**. These control signals (c1, c2, c3, c4, c5, and c6) can correspond to gate control signals G1, G2, G3, G4, G5, and G6 as shown in Figure 6 (and referenced in Figure 8).

[0040] Additionally, the inverter controller **410** optionally uses current and/or power

sensing feedback **411** from the resonant tank **408** to adjust the control signals.

[0041] Figure 7 is an example inverter controller. The illustrated example inverter controller can implement the inverter controller **410** illustrated in Figure 4A as an example. Referring to Figure 7, an example implementation of an inverter controller **700** includes a phase
5 detector **710** that receives the three phase input signal A, B, and C from the three phase power source and a gate driver **720** that outputs appropriate control signals c1, c2, c3, c4, c5, and c6 based on the detected phase output from the phase detector **710** and, optionally, the signal from a current or power regulator **730**. When packaged together with the direct three phase inverter (e.g., as in the example illustrated in Figures 2A and 2C), the phase detector **710** can receive the three
10 phase input signals from a same input power line(s). When packaged separately from the direct three phase inverter (e.g., as in the example illustrated in Figure 2B), separate connections to the three phase input signal A, B, and C are used.

[0042] The gate driver **720** can include gate driving logics **721** and an adaptive one-shot gate driving circuit **722**. Additional detail regarding the adaptive one-shot gate driving circuit **722**
15 and method related thereto is provided in reference to Figures 10A and 10B. The current or power regulator **730** enables the inverter controller to monitor the current (I), power (P), or both current and power, and maintain, compensate or otherwise adjust the output current (and/or power).

[0043] Figure 8 illustrates an example implementation of an inverter controller such as inverter controller **700**. As shown in Figure 8, the three phase input signal (via V_A, V_B, and V_C)
20 is detected using logic or processor for AC Phase Detection **810**, the output of which providing six signals to gate driving logic **820** that controls which gates to drive according to the appropriate phase region. Feedback in the form of sensed current and sensed power from the output of a direct three phase inverter is provided to a comparator **830** and voltage controlled oscillator (VCO) **840** to facilitate adjustments for output current and/or output power. The output of the VCO **840** is
25 used to trigger an adaptive one shot circuit **850** (discussed in more detail with respect to the specific implementation shown in Figures 14A-14F). The pulse signal generated by the adaptive one shot circuit **850** and the output of the gate driving logic **820** are used as input to the adaptive one-shot gate drivers **860** that generate control signals (e.g., G1, G2, G3, G4, G5, G6) for the switches.

[0044] Figure 9 illustrates an example process carried out by an inverter controller. Referring to Figure 9, a process **900** can be carried out at an inverter controller such as described with respect to any of Figures 4A, 7, and 8 to facilitate the direct three phase parallel resonant inverter for reactive gas generating applications. Indeed, process **900** (and thereby the inverter controller) can be implemented using a micro-processor, digital signal processor (DSP), complex
30

programmable logic device (CPLD), field programmable gate array (FPGA), logic, or a combination thereof.

[0045] The inverter controller can detect the phase of each signal (e.g., V_a , V_b , V_c shown in Figures 6 and 8) of the three-phase ac input (910). This may be carried out, for example, using phase detector 710 of Figure 7 or phase detector 810 of Figure 8. The inverter controller can further receive sensed output power and/or output current (920). The output power, output current, or both output power and output current can be detected via circuitry coupled to the output of the direct three phase inverter (e.g., via a current or power regulator 730 connected to a load including resonant tank and/or plasma generator). Based on the detected phase (and the sensed power and/or current output), control signals can be generated (930).

[0046] According to an implementation, generating the control signals includes, from the time when V_a is equal to V_c , and until the time when V_a is equal to V_b (where V_a , V_b , and V_c are the phases detected previously in 910), alternating between turning on Q2 and Q3 and turning on Q5 and Q6 so that Q2 and Q3 are on while Q5 and Q6 are turned off and vice versa (931). Then, from the time when V_a is equal to V_b , and until the time when V_b is equal to V_c , alternating between turning on Q1 and Q2 and turning on Q4 and Q5 so that Q1 and Q2 are on while Q4 and Q5 are turned off and vice versa (932). Then, from the time when V_b is equal to V_c , and until the time when V_a is equal to V_c , alternating between turning on Q1 and Q3 and turning on Q4 and Q6 so that Q1 and Q3 are on while Q4 and Q6 are turned off and vice versa (933). As V_a is detected to be equal to V_c (and while the system is in operation), steps 931, 932, and 933 repeat.

[0047] During this time, the received sensed output power and/or output current are used to adjust the length of OFF time in response to power needs while providing an adaptive ON time (934). The signals identifying which of the transistors should be turned on are combined with the driving signal generated from step 934 to output control signals with modulated OFF time (940). In addition, even though a pair of switches may be identified at steps 931, 932, and 933 to be turned on, the driving signal may actually not have both switches ON at the same time. An adaptive one shot circuit can be used to facilitate the “constant” ON time control with modulated OFF time. This process enables a constant ON time control where the OFF time is modulated and the ON time is adapted (for adaptive ON time).

[0048] As an illustrative example, an inverter controller, can monitor the three phases V_a , V_b , and V_c ; and, in response to an indication of $V_a = V_c$ and until $V_a = V_b$, generate a signal maintaining the Q1 and Q4 in an OFF state, alternately generate a signal indicating both Q2 and Q3 are active and both Q5 and Q6 are active, and generate the appropriate driving signals to the active pair. The control signals for Q2, Q3, Q5, and Q6 can have a constant ON time, but an OFF

time based on desired output power or output current. In addition, in response to an indication of $V_a = V_b$ and until $V_b = V_c$, the inverter controller can generate a signal maintaining Q3 and Q6 in the OFF state, alternately generate a signal indicating both Q1 and Q2 are active and both Q4 and Q5 are active, and generate the appropriate driving signals to the active pair. The control signals for Q1, Q2, Q4, and Q5 have a constant ON time, but an OFF time based on desired output power. Then, in response to an indication of $V_b = V_c$ and until $V_c = V_a$, the inverter controller can generate a signal maintaining Q2 and Q5 in the OFF state, alternately generate a signal indicating that both Q1 and Q3 are active and both Q4 and Q6 are active, and generate the appropriate driving signals to the active pair.

[0049] Figures 10A and 10B illustrate adaptive ON time control. In particular, Figures 10A and 10B provide a snapshot comparison of signals occurring, for example, during the time of either step 932 or 933 of Figure 9 and in response to step 934 of Figure 9 when applied to a system including a direct three phase inverter such as shown in Figure 6. That is, Q1 and Q4 are turned on and off with gate control signals G1 and G4, where the length of OFF time is adjusted in response to power needs (e.g., for plasma applicator 110) while maintaining “fixed” ON time (of an adaptive, constant ON time). Here, the power needs are shown as a “low” plasma power of 4 kW and a “high” plasma power of 8 kW. First, referring to Figure 10A, voltage-time graphs of the gate control signals G1 and G4 output at step 940 of Figure 9 shows the ON time for G1 and G4 as about 2 μ s and OFF time as about 6 μ s (see voltage-time plot for G4). The corresponding voltage (V_{ds}) and current ($I(R_{ds})$) across the transistors Q1 and Q4 are illustrated in the V/I plots.

[0050] As a comparison, the length of OFF time can be modulated (for example using an adaptive one-shot circuit) and the results shown in Figure 10B. Referring to Figure 10B, it can be seen that the ON time for G1 and G4 remains about 2 μ s; however, the OFF time has been adjusted to about 3 μ s, which is half of the OFF time of the scenario shown in Figure 10A. The doubling of the power output (from 4 kW to 8 kW) can be achieved by this shortening of the OFF time. With the constant ON time, the current through the transistor can be more easily minimized (and provide a more consistent output) both at the turning on and turning off of the transistor.

[0051] Figure 11A illustrates a simplified control logic for basic driver operation; and Figure 11B provides a timing diagram representation for the basic driver operation of the simplified control logic of Figure 11A. The control logic 1100 may be implemented at an inverter controller. Here, the control logic 1100 receives signals Q1s, Q2s, Q3s, Q4s, Q5s, and Q6s for selecting particular switches to turn on and off at the inverter. These signals may be based on a detected phase of the three phase AC supply, illustrated as V_a , V_b , and V_c in the timing diagram of Figure 11B. In addition, the control logic 1100 receives clock signals QP and QN. It can be

noted that when the implementation includes an adaptive one shot circuit, the clock signals QP and QN for this basic driver operation can be replaced with the pulses from the adaptive one shot circuit. The output of the control logic **1100** drives the switches Q1, Q2, Q3, Q4, Q5, and Q6 as illustrated in Figure 11B.

5 [0052] Figure 12 provides a detailed snapshot of the simplified timing diagram of Figure 11B from t_1 to t_2 ; and Figures 13A-13D illustrate current flow and operation of an inverter in response to the gate driving logic operations shown in the simplified timing diagram of Figure 12. The simplified timing diagram of Figure 12 also shows the inverter's output voltage (V_{inv}) and output current (I_{inv}). The operation of the inverter can be identified by particular windows of
 10 time, which are reflected in the Figures 13A-13D. Here, Figure 13A illustrates the inverter operation during t_1 to t_{1-1} , where Q2 and Q3 are ON and current is "positive" (in the direction of the arrow). Next, Figure 13B illustrates the inverter operation during t_{1-1} to t_{1-2} , where Q2 and Q3 are still ON, but the current becomes negative (see change in signal path through diodes). Then, from t_{1-2} to t_{1-3} , Q5 and Q6 are turned on, Q2 and Q3 are turned OFF and the current is still negative
 15 (based on signal path through diodes), as shown in Figure 13C. Then, as shown in Figure 13D, from t_{1-3} to t_{1-4} , Q5 and Q6 remain ON, but the current becomes positive again. This sequence continues to repeat from t_{1-4} to t_2 .

[0053] Example Simulations

[0054] Figures 14A-14F show a schematic of a plasma generating system with a direct
 20 three phase parallel resonant inverter from which simulations were carried out. Figure 14A shows a simulated three phase 208VAC supply **1401**, direct three phase inverter **1402** with six switches (see also Figure 6), a parallel resonant tank **1403** (see also e.g., Figure 3A), and simulated plasma applicator **1404**. Figure 14B shows a simulated three phase 208VAC phase detector **1405** that couples to the A, B, and C nodes of the simulated three phase 208VAC supply **1401** and outputs
 25 P1, P2, P3, P4, P5, and P6 signals that are used by the initial stage **1411** of the driving circuit **1410** shown in Figure 14E. Figure 14C shows a simulated Isense/Psense power/current loop from a plasma generator (from Inv_rms of 14A) and power/current loop compensator (PI Comp) **1406**. Depending on the configuration, a power loop or current loop from the plasma generator may be used. As illustrated in the example shown in Figure 14C, the power loop (from input node
 30 "Power") is closed and the output of the proportional plus integral controller (the PI Comp **1406**) is a frequency command. The output of the PI Comp **1406** provides the frequency command of frequency signal/clock (freq) for the one shot timer **1407** for adaptive one-shot and adaptive ON time (VCO) shown in Figure 14D. Referring to Figure 14D, after receiving the frequency command, the output of the one shot timer **1407** includes OUTA, OUTB, OUTC, and OUTD,

which are signals used by the one shot gate driving circuit stage **1412** (see also e.g., Figure 11A which uses clock signals instead of the adaptive one-shot) of the driving circuit **1410** shown in Figure 14E.

[0055] As shown in Figure 14E, the driving circuit receives the outputs indicative of the phase (P1, P2, P3, P4, P5, and P6) and the outputs of the one shot timer (OUTA, OUTB, OUTC, and OUTD) to generate intermediate gate control signals G1a, G2a, G3a, G4a, G5a, and G6a. Figure 14F shows the driver output rectifier that receives the intermediate gate control signals G1a, G2a, G3a, G4a, G5a, and G6a and outputs the gate control signals G1, G2, G3, G4, G5, and G6.

[0056] Figures 15A-15K show plots of simulation results from the schematic of Figures 14A-14F for a full 15 kW output load; and Figures 16A-16K show plots of simulation results from the schematic of Figures 14A-14F for a 5 kW output load. Figures 15A and 16A show the current and the voltage (V_{DS}) across transistor Q1 while the three phase 208VAC signals are as shown in Figures 15E and 16E; Figures 15B and 16B show, for the same window of time, the current and the voltage across transistor Q4, which is paired with Q1 in connection to one of the three phase signal lines from the power supply. Figures 15C and 16C show the voltage and current at the output of the plasma generator; and Figures 15D and 16D show the resulting output plasma power, confirming output power of 15 kW and 5 kW, respectively.

[0057] Figures 15F and 16F show a snippet of the current and voltage across transistor Q1 during the 10 μ s window as shown in Figures 15J and 16J; and Figures 15G and 16G show a snippet of the current and voltage across transistor Q4 across this same window. Figures 15H and 16H show the plasma current and plasma voltage (for this window of time); and Figures 15I and 16I show the resulting output plasma power. As can be seen from where I_{ds} and V_{ds} cross in Figures 15F, 15G, 16F, and 16G, the power stage described in various implementations herein can achieve nearly zero current switching (ZCS) for both turn ON (see arrow with solid line) and turn OFF (see arrow with dotted line), and thereby provide lossless power devices power dissipation.

[0058] Figures 15K and 16K provide additional detail. The adaptive one-shot and adaptive ON time circuitry uses the frequency information from the signal freq to modulate the OFF time while slightly increasing the ON time at light loads. Referring to Figure 15K, for a 1 kW plasma load, the ON time is 1.79 μ s and the ON time is 26.5 μ s at the one-shot timer signal OUTD (see Figure 14D). At the heavier loads, such as for an 11 kW plasma load, the ON time in the simulation is 1.43 μ s and OFF time is 2.39 μ s at the one-shot time signal OUTD. Accordingly, it can be seen that the adaptive ON time circuitry (using the frequency control signal freq) results in the length of ON time to be relatively constant (with a slight change from 1.79 μ s to 1.43 μ s) while the OFF

time is modulated from 26.5 μ s to 2.39 μ s.

[0059] Certain aspects of the invention provide the following non-limiting embodiments:

[0060] Example 1. A power system comprising: a direct three phase inverter having a first phase input line, a second phase input line, and a third phase input line for receiving a three phase AC input; and a resonant tank receiving an output of the direct three phase inverter.

[0061] Example 2. The power system of example 1, wherein the output of the direct three phase inverter is provided via a first output line and a second output line, wherein the direct three phase inverter comprises six uni-directional switches, one uni-directional switch connecting the first phase input line to the first output line, one uni-directional switch connecting the first phase input line to the second output line, one uni-directional switch connecting the second phase input line to the first output line, one uni-directional switch connecting the second phase input line to the second output line, one uni-directional switch connecting the third phase input line to the first output line, and one uni-directional switch connecting the third phase input line to the second output line.

[0062] Example 3. The power system of example 2, wherein each of the six uni-directional switches comprises a power transistor and four diodes.

[0063] Example 4. The power system of example 3, wherein the power transistor is a metal-oxide-semiconductor field-effect transistor, bipolar junction transistor, insulated-gate bipolar transistor or silicon carbide transistor.

[0064] Example 5. The power system of example 2, wherein each of the six uni-directional switches comprises two metal-oxide-semiconductor field-effect transistors (MOSFETs), the two MOSFETs being coupled at their gates and their sources.

[0065] Example 6. The power system of any of examples 2-5, further comprising an inverter controller connected to the first phase input line, the second phase input line, and the third phase input line for receiving the three phase AC input; wherein the inverter controller has a first signal line coupled to the first uni-directional switch to control the first uni-directional switch, a second signal line coupled to the second uni-directional switch to control the second uni-directional switch, a third signal line coupled to the third uni-directional switch to control the third uni-directional switch, a fourth signal line coupled to the fourth uni-directional switch to control the fourth uni-directional switch, a fifth signal line coupled to the fifth uni-directional switch to control the fifth uni-directional switch, and a sixth signal line coupled to the sixth uni-directional switch to control the sixth uni-directional switch, wherein the inverter controller comprises logic that: in response to an indication of a first phase of the three phase AC input being equal to a third phase of the three phase AC input, maintains the first uni-directional switch and the fourth uni-

directional switch in an OFF state and alternates between turning on and off both the second uni-directional switch and the third uni-directional switch and turning on and off both the fifth uni-directional switch and the sixth uni-directional switch; in response to an indication of the first phase being equal to a second phase of the three phase AC input, maintains the third uni-directional switch and the sixth uni-directional switch in the OFF state and alternates between turning on and off both the first uni-directional switch and the second uni-directional switch and turning on and off both the fourth uni-directional switch and the fifth uni-directional switch; and in response to an indication of the second phase being equal to the third phase, maintains the second uni-directional switch and the fourth uni-directional switch in the OFF state and alternates between turning on and off both the first uni-directional switch and the third uni-directional switch and turning on and off both the fourth uni-directional switch and the sixth uni-directional switch.

[0066] Example 7. The power system of example 6, wherein the inverter controller is coupled to the resonant tank to receive a sensed output current and a sensed output power from the resonant tank, wherein the inverter controller further comprises logic that, while providing an adaptive ON time, modulates an amount of OFF time for each of the first, second, third, fourth, fifth, and sixth uni-directional switches based on the sensed output current and the sensed output power.

[0067] Example 8. A power system comprising: a direct three phase inverter having a first phase input line, a second phase input line, and a third phase input line for receiving a three phase AC input; and an inverter controller connected to the first phase input line, the second phase input line, and the third phase input line for receiving the three phase AC input and controlling the direct three phase inverter based on states of the three phase AC input.

[0068] Example 9. The power system of example 8, wherein the direct three phase inverter comprises six uni-directional switches, one uni-directional switch connecting the first phase input line to a first output line of the direct three phase inverter when turned on by the inverter controller, one uni-directional switch connecting the first phase input line to a second output line of the direct three phase inverter when turned on by the inverter controller, one uni-directional switch connecting the second phase input line to the first output line when turned on by the inverter controller, one uni-directional switch connecting the second phase input line to the second output line when turned on by the inverter controller, one uni-directional switch connecting the third phase input line to the first output line when turned on by the inverter controller, and one uni-directional switch connecting the third phase input line to the second output line when turned on by the inverter controller.

[0069] Example 10. The power system of example 9, wherein each of the six uni-

directional switches comprises a power transistor and four diodes.

[0070] Example 11. The power system of example 9, wherein each of the six uni-directional switches comprises two metal-oxide-semiconductor field-effect transistors (MOSFETs), the two MOSFETs being coupled at their gates and their sources.

5 [0071] Example 12. The power system of any of examples 8-11, wherein the inverter controller comprises: a phase detector; and a gate driver comprising gate driving logics and an adaptive one-shot gate driving circuit.

[0072] Example 13. The power system of example 12, wherein the inverter controller further comprises a current/power regulator and a voltage controlled oscillator, wherein the
10 voltage controlled oscillator outputs a signal having a frequency based on a sensed power and sensed current received via the current/power regulator, wherein the adaptive one-shot gate driving circuit receives the signal having the frequency and generates a driving signal that modulates a length of OFF time while providing an adaptive ON time.

[0073] Example 14. The power system of example 12 or 13, wherein the phase detector
15 receives the three phase AC input and outputs corresponding voltages representative of each signal of the three phase AC input, wherein the gate driving logics comprises logic that receives the corresponding voltages representative of each signal of the three phase AC input and turns on particular switches of the direct three phase inverter based on a phase state of the signals of the three phase AC input.

20 [0074] Example 15. The power system of example 14, wherein the logic that receives the corresponding voltages representative of each signal of the three phase AC input and turns on particular switches of the direct three phase inverter based on a phase state of the signals of the three phase AC input comprises logic that: in response to an indication of a first phase of the three phase AC input being equal to a third phase of the three phase AC input, maintains the first uni-
25 directional switch and the fourth uni-directional switch in an OFF state and alternates between turning on and off both the second uni-directional switch and the third uni-directional switch and turning on and off both the fifth uni-directional switch and the sixth uni-directional switch; in response to an indication of the first phase being equal to a second phase of the three phase AC input, maintains the third uni-directional switch and the sixth uni-directional switch in the OFF
30 state and alternates between turning on and off both the first uni-directional switch and the second uni-directional switch and turning on and off both the fourth uni-directional switch and the fifth uni-directional switch; and in response to an indication of the second phase being equal to the third phase, maintains the second uni-directional switch and the fourth uni-directional switch in the OFF state and alternates between turning on and off both the first uni-directional switch and

the third uni-directional switch and turning on and off both the fourth uni-directional switch and the sixth uni-directional switch.

[0075] Example 16. A power system for plasma applications, the power system comprising: a direct three phase inverter having a first phase input line, a second phase input line, and a third phase input line for receiving a three phase AC input; a resonant tank receiving an output of the direct three phase inverter to generate a sine-wave output; and an inverter controller supplying control signals to the direct three phase inverter, the inverter controller being connected to the first phase input line, the second phase input line, and the third phase input line for receiving the three phase AC input and being coupled to the resonant tank to receive a sensed output power and sensed output current.

[0076] Example 17. The power system of example 16, wherein the inverter controller reduces output power to a plasma applicator by increasing OFF time of the control signals supplied to the direct three phase inverter; and wherein the inverter controller increases output power to the plasma applicator by decreasing OFF time of the control signals.

[0077] Example 18. The power system of example 17, wherein the inverter controller comprises an adaptive one-shot gate driving circuit that provides an adaptive ON time while modulating the OFF time of the control signals based on the sensed output power and the sensed output current.

[0078] Example 19. The power system of any of examples 16-18, wherein the output of the direct three phase inverter is provided via a first output line and a second output line, wherein the direct three phase inverter comprises six uni-directional switches, one uni-directional switch connecting the first phase input line to the first output line, one uni-directional switch connecting the first phase input line to the second output line, one uni-directional switch connecting the second phase input line to the first output line, one uni-directional switch connecting the second phase input line to the second output line, one uni-directional switch connecting the third phase input line to the first output line, and one uni-directional switch connecting the third phase input line to the second output line; wherein the inverter controller has a first signal line coupled to the first uni-directional switch to control the first uni-directional switch, a second signal line coupled to the second uni-directional switch to control the second uni-directional switch, a third signal line coupled to the third uni-directional switch to control the third uni-directional switch, a fourth signal line coupled to the fourth uni-directional switch to control the fourth uni-directional switch, a fifth signal line coupled to the fifth uni-directional switch to control the fifth uni-directional switch, and a sixth signal line coupled to the sixth uni-directional switch to control the sixth uni-directional switch, wherein the inverter controller comprises logic that: in response to an

indication of a first phase of the three phase AC input being equal to a third phase of the three phase AC input, maintains the first uni-directional switch and the fourth uni-directional switch in an OFF state and alternates between turning on and off both the second uni-directional switch and the third uni-directional switch and turning on and off both the fifth uni-directional switch and the sixth uni-directional switch; in response to an indication of the first phase being equal to a second phase of the three phase AC input, maintains the third uni-directional switch and the sixth uni-directional switch in the OFF state and alternates between turning on and off both the first uni-directional switch and the second uni-directional switch and turning on and off both the fourth uni-directional switch and the fifth uni-directional switch; and in response to an indication of the second phase being equal to the third phase, maintains the second uni-directional switch and the fourth uni-directional switch in the OFF state and alternates between turning on and off both the first uni-directional switch and the third uni-directional switch and turning on and off both the fourth uni-directional switch and the sixth uni-directional switch.

[0079] Example 20. A method of supplying power to a reactive gas generator, comprising: providing a direct three phase inverter to directly receive a three phase AC input via a first phase input line, a second phase input line, and a third phase input line; and operating the direct three phase inverter according to states of the three phases of the three phase AC input.

[0080] Example 21. The method of example 20, further comprising: generating a sine wave output by providing a resonant tank coupled to an output of the direct three phase inverter.

[0081] Example 22. The method of example 20 or 21, further comprising: providing an inverter controller connected to receive the three phase AC input, the inverter controller operating the direct three phase inverter according to the states of the three phases of the three phase AC input.

[0082] Example 23. The method of example 22, further comprising: generating a one-shot driving signal at the inverter controller; and using the one-shot driving signal as a driving signal to turn on a switch of the direct three phase inverter with an adaptive ON time (e.g., a relatively constant ON time) and a modulated OFF time.

[0083] Example 24. The method of example 22 or 23, wherein operating the direct three phase inverter according to the states of the three phases of the three phase AC input comprises: in response to an indication of a first phase of the three phase AC input being equal to a third phase of the three phase AC input: generating an OFF signal to maintain a first switch and a fourth switch of the direct three phase inverter, which are coupled to the first phase input line, in an OFF state; and generating driving signals that alternately turn on and off both a second switch of the direct three phase inverter, which is coupled to the third phase input line, and a third switch of the

direct three phase inverter, which is coupled to the second phase input line, and turn on and off both a fifth switch of the direct three phase inverter, which is coupled to the third phase input line, and a sixth switch of the direct three phase inverter, which is coupled to the second phase input line; in response to an indication of the first phase being equal to a second phase of the three phase
5 AC input: generating the OFF signal to maintain the third switch and the sixth switch in the OFF state; and generating driving signals that alternately turn on and off both the first switch and the second switch and turn on and off both the fourth switch and the fifth switch; and in response to an indication of the second phase being equal to the third phase: generating the OFF signal to maintain the second switch and the fourth switch in the OFF state, and generating driving signals
10 that alternately turn on and off both the first switch and the third switch and turn on and off both the fourth switch and the sixth switch.

[0084] Example 25. The method of example 24, further comprising: generating one-shot driving signals at the inverter controller; and using the one-shot driving signals as the driving signals to turn on and off appropriate ones of the first switch, second switch, third switch, fourth
15 switch, fifth switch, and sixth switch of the direct three phase inverter with an adaptive ON time (e.g., a relatively constant ON time) and a modulated OFF time.

[0085] Example 26. A method of supplying power: comprising performing a method according to any of examples 20-25.

[0086] Example 27. A method of supplying power: comprising providing a power system
20 of any of examples 1-19.

[0087] It should be understood that the examples, implementations, and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

CLAIMS

What is claimed is:

1. A power system comprising:
 - a direct three phase inverter having a first phase input line, a second phase input line, and a third phase input line for receiving a three phase AC input; and
 - a resonant tank receiving an output of the direct three phase inverter.
2. The power system of claim 1, wherein the output of the direct three phase inverter is provided via a first output line and a second output line,
 - wherein the direct three phase inverter comprises six uni-directional switches, one uni-directional switch connecting the first phase input line to the first output line, one uni-directional switch connecting the first phase input line to the second output line, one uni-directional switch connecting the second phase input line to the first output line, one uni-directional switch connecting the second phase input line to the second output line, one uni-directional switch connecting the third phase input line to the first output line, and one uni-directional switch connecting the third phase input line to the second output line.
3. The power system of claim 2, wherein each of the six uni-directional switches comprises a power transistor and four diodes.
4. The power system of claim 3, wherein the power transistor is a metal-oxide-semiconductor field-effect transistor, bipolar junction transistor, insulated-gate bipolar transistor or silicon carbide transistor.
5. The power system of claim 2, wherein each of the six uni-directional switches comprises two metal-oxide-semiconductor field-effect transistors (MOSFETs), the two MOSFETs being coupled at their gates and their sources.
6. The power system of claim 2, further comprising an inverter controller connected to the first phase input line, the second phase input line, and the third phase input line for receiving the three phase AC input;
 - wherein the inverter controller has a first signal line coupled to the first uni-directional switch to control the first uni-directional switch, a second signal line coupled to the second uni-directional switch to control the second uni-directional switch, a third signal line coupled to the third uni-directional switch to control the third uni-directional switch, a fourth signal line coupled to the fourth uni-directional switch to control the fourth uni-directional switch, a fifth signal line coupled to the fifth uni-directional switch to control the fifth uni-directional switch, and a sixth signal line coupled to the sixth uni-directional switch to control the sixth uni-directional switch,
 - wherein the inverter controller comprises logic that:

in response to an indication of a first phase of the three phase AC input being equal to a third phase of the three phase AC input, maintains the first uni-directional switch and the fourth uni-directional switch in an OFF state and alternates between turning on and off both the second uni-directional switch and the third uni-directional switch and turning on and off both the fifth uni-directional switch and the sixth uni-directional switch;

in response to an indication of the first phase being equal to a second phase of the three phase AC input, maintains the third uni-directional switch and the sixth uni-directional switch in the OFF state and alternates between turning on and off both the first uni-directional switch and the second uni-directional switch and turning on and off both the fourth uni-directional switch and the fifth uni-directional switch; and

in response to an indication of the second phase being equal to the third phase, maintains the second uni-directional switch and the fourth uni-directional switch in the OFF state and alternates between turning on and off both the first uni-directional switch and the third uni-directional switch and turning on and off both the fourth uni-directional switch and the sixth uni-directional switch.

7. The power system of claim 6, wherein the inverter controller is coupled to the resonant tank to receive a sensed output current and a sensed output power from the resonant tank, wherein the inverter controller further comprises logic that, while providing an adaptive ON time, modulates an amount of OFF time for each of the first, second, third, fourth, fifth, and sixth uni-directional switches based on the sensed output current and the sensed output power.

8. A power system comprising:

a direct three phase inverter having a first phase input line, a second phase input line, and a third phase input line for receiving a three phase AC input; and

an inverter controller connected to the first phase input line, the second phase input line, and the third phase input line for receiving the three phase AC input and controlling the direct three phase inverter based on states of the three phase AC input.

9. The power system of claim 8, wherein the inverter controller comprises:

a phase detector; and

a gate driver comprising gate driving logics and an adaptive one-shot gate driving circuit.

10. The power system of claim 9, wherein the inverter controller further comprises a current/power regulator and a voltage controlled oscillator, wherein the voltage controlled oscillator outputs a signal having a frequency based on a sensed power and sensed current received via the current/power regulator, wherein the adaptive one-shot gate driving circuit receives the signal having the frequency and generates a driving signal that modulates a length of OFF time

while providing an adaptive ON time.

11. The power system of claim 9, wherein the phase detector receives the three phase AC input and outputs corresponding voltages representative of each signal of the three phase AC input, wherein the gate driving logics comprises logic that receives the corresponding voltages representative of each signal of the three phase AC input and turns on particular switches of the direct three phase inverter based on a phase state of the signals of the three phase AC input.

12. The power system of claim 11, wherein the direct three phase inverter comprises six uni-directional switches, one uni-directional switch connecting the first phase input line to a first output line of the direct three phase inverter when turned on by the inverter controller, one uni-directional switch connecting the first phase input line to a second output line of the direct three phase inverter when turned on by the inverter controller, one uni-directional switch connecting the second phase input line to the first output line when turned on by the inverter controller, one uni-directional switch connecting the second phase input line to the second output line when turned on by the inverter controller, one uni-directional switch connecting the third phase input line to the first output line when turned on by the inverter controller, and one uni-directional switch connecting the third phase input line to the second output line when turned on by the inverter controller.

13. The power system of claim 12, wherein the logic that receives the corresponding voltages representative of each signal of the three phase AC input and turns on particular switches of the direct three phase inverter based on a phase state of the signals of the three phase AC input comprises logic that:

in response to an indication of a first phase of the three phase AC input being equal to a third phase of the three phase AC input, maintains the first uni-directional switch and the fourth uni-directional switch in an OFF state and alternates between turning on and off both the second uni-directional switch and the third uni-directional switch and turning on and off both the fifth uni-directional switch and the sixth uni-directional switch;

in response to an indication of the first phase being equal to a second phase of the three phase AC input, maintains the third uni-directional switch and the sixth uni-directional switch in the OFF state and alternates between turning on and off both the first uni-directional switch and the second uni-directional switch and turning on and off both the fourth uni-directional switch and the fifth uni-directional switch; and

in response to an indication of the second phase being equal to the third phase, maintains the second uni-directional switch and the fourth uni-directional switch in the OFF state and alternates between turning on and off both the first uni-directional switch

and the third uni-directional switch and turning on and off both the fourth uni-directional switch and the sixth uni-directional switch.

14. The power system of claim 12, wherein each of the six uni-directional switches comprises a power transistor and four diodes.

15. The power system of claim 12, wherein each of the six uni-directional switches comprises two metal-oxide-semiconductor field-effect transistors (MOSFETs), the two MOSFETs being coupled at their gates and their sources.

16. A power system for plasma applications, the power system comprising:

a direct three phase inverter having a first phase input line, a second phase input line, and a third phase input line for receiving a three phase AC input;

a resonant tank receiving an output of the direct three phase inverter to generate a sine-wave output; and

an inverter controller supplying control signals to the direct three phase inverter, the inverter controller being connected to the first phase input line, the second phase input line, and the third phase input line for receiving the three phase AC input and being coupled to the resonant tank to receive a sensed output power and sensed output current.

17. The power system of claim 16, wherein the inverter controller reduces output power to a plasma applicator by increasing OFF time of the control signals supplied to the direct three phase inverter; and wherein the inverter controller increases output power to the plasma applicator by decreasing OFF time of the control signals.

18. The power system of claim 17, wherein the inverter controller comprises an adaptive one-shot gate driving circuit that provides an adaptive ON time while modulating the OFF time of the control signals based on the sensed output power and the sensed output current.

19. The power system of claim 16, wherein the output of the direct three phase inverter is provided via a first output line and a second output line,

wherein the direct three phase inverter comprises six uni-directional switches, one uni-directional switch connecting the first phase input line to the first output line, one uni-directional switch connecting the first phase input line to the second output line, one uni-directional switch connecting the second phase input line to the first output line, one uni-directional switch connecting the second phase input line to the second output line, one uni-directional switch connecting the third phase input line to the first output line, and one uni-directional switch connecting the third phase input line to the second output line;

wherein the inverter controller has a first signal line coupled to the first uni-directional switch to control the first uni-directional switch, a second signal line coupled to the second uni-

directional switch to control the second uni-directional switch, a third signal line coupled to the third uni-directional switch to control the third uni-directional switch, a fourth signal line coupled to the fourth uni-directional switch to control the fourth uni-directional switch, a fifth signal line coupled to the fifth uni-directional switch to control the fifth uni-directional switch, and a sixth signal line coupled to the sixth uni-directional switch to control the sixth uni-directional switch, wherein the inverter controller comprises logic that:

in response to an indication of a first phase of the three phase AC input being equal to a third phase of the three phase AC input, maintains the first uni-directional switch and the fourth uni-directional switch in an OFF state and alternates between turning on and off both the second uni-directional switch and the third uni-directional switch and turning on and off both the fifth uni-directional switch and the sixth uni-directional switch;

in response to an indication of the first phase being equal to a second phase of the three phase AC input, maintains the third uni-directional switch and the sixth uni-directional switch in the OFF state and alternates between turning on and off both the first uni-directional switch and the second uni-directional switch and turning on and off both the fourth uni-directional switch and the fifth uni-directional switch; and

in response to an indication of the second phase being equal to the third phase, maintains the second uni-directional switch and the fourth uni-directional switch in the OFF state and alternates between turning on and off both the first uni-directional switch and the third uni-directional switch and turning on and off both the fourth uni-directional switch and the sixth uni-directional switch.

20. A method of supplying power to a reactive gas generator, comprising:

providing a direct three phase inverter to directly receive a three phase AC input via a first phase input line, a second phase input line, and a third phase input line; and

operating the direct three phase inverter according to states of the three phases of the three phase AC input.

21. The method of claim 20, further comprising:

generating a sine wave output by providing a resonant tank coupled to an output of the direct three phase inverter.

22. The method of claim 20, further comprising:

providing an inverter controller connected to receive the three phase AC input, the inverter controller operating the direct three phase inverter according to the states of the three phases of the three phase AC input.

23. The method of claim 22, further comprising:

generating a one-shot driving signal at the inverter controller; and

using the one-shot driving signal as a driving signal to turn on a switch of the direct three phase inverter with an adaptive ON time and a modulated OFF time.

24. The method of claim 22, wherein operating the direct three phase inverter according to the states of the three phases of the three phase AC input comprises:

in response to an indication of a first phase of the three phase AC input being equal to a third phase of the three phase AC input:

generating an OFF signal to maintain a first switch and a fourth switch of the direct three phase inverter, which are coupled to the first phase input line, in an OFF state; and

generating driving signals that alternately turn on and off both a second switch of the direct three phase inverter, which is coupled to the third phase input line, and a third switch of the direct three phase inverter, which is coupled to the second phase input line, and turn on and off both a fifth switch of the direct three phase inverter, which is coupled to the third phase input line, and a sixth switch of the direct three phase inverter, which is coupled to the second phase input line;

in response to an indication of the first phase being equal to a second phase of the three phase AC input:

generating the OFF signal to maintain the third switch and the sixth switch in the OFF state; and

generating driving signals that alternately turn on and off both the first switch and the second switch and turn on and off both the fourth switch and the fifth switch; and

in response to an indication of the second phase being equal to the third phase:

generating the OFF signal to maintain the second switch and the fourth switch in the OFF state, and

generating driving signals that alternately turn on and off both the first switch and the third switch and turn on and off both the fourth switch and the sixth switch.

25. The method of claim 24, further comprising:

generating one-shot driving signals at the inverter controller; and

using the one-shot driving signals as the driving signals to turn on and off appropriate ones of the first switch, second switch, third switch, fourth switch, fifth switch, and sixth switch of the direct three phase inverter with an adaptive ON time and a modulated OFF time.

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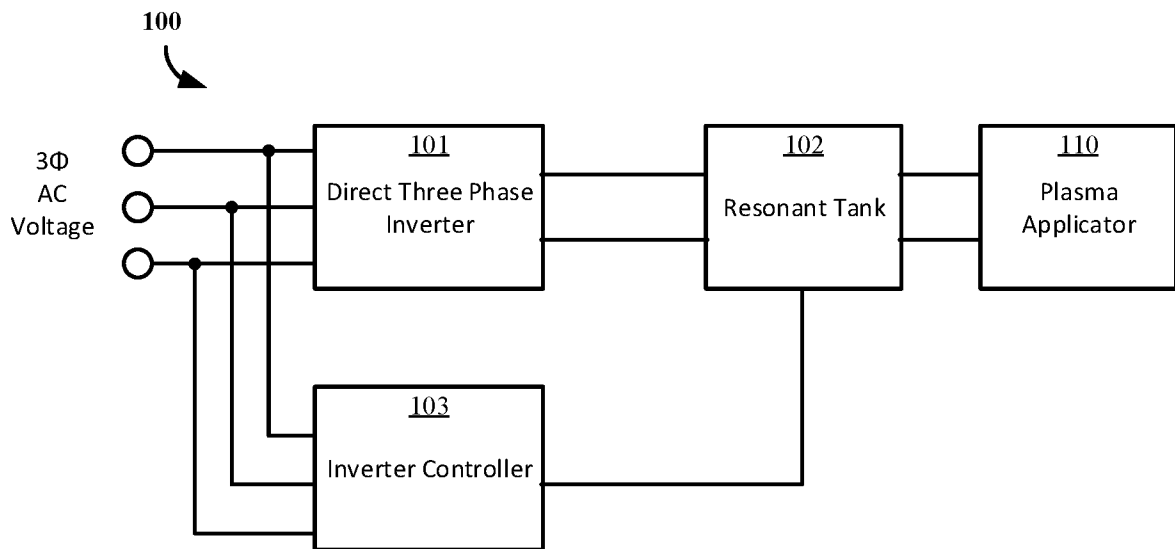


FIG. 1

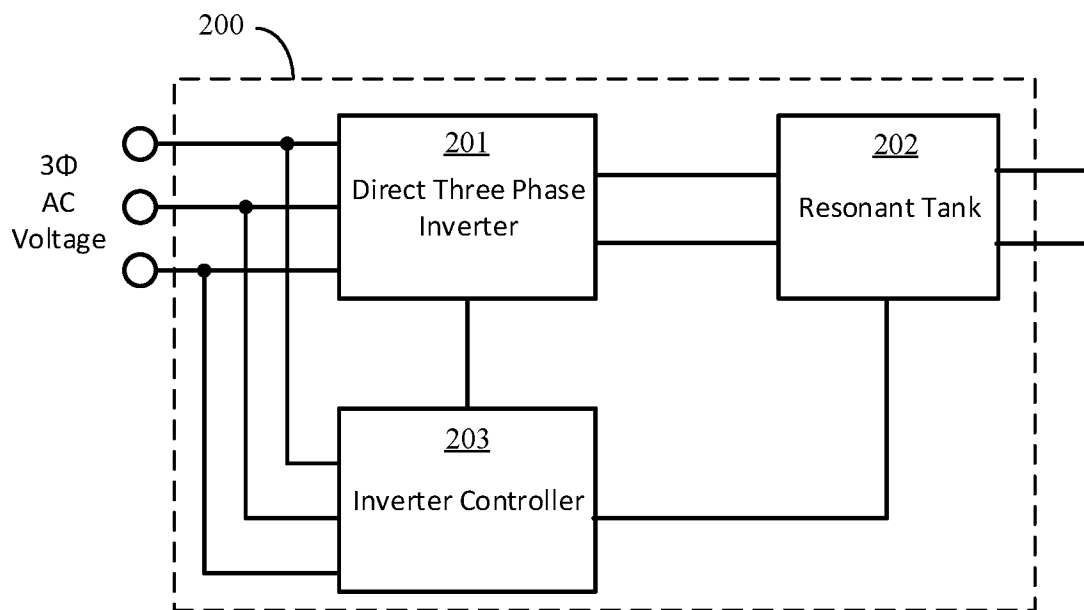


FIG. 2A

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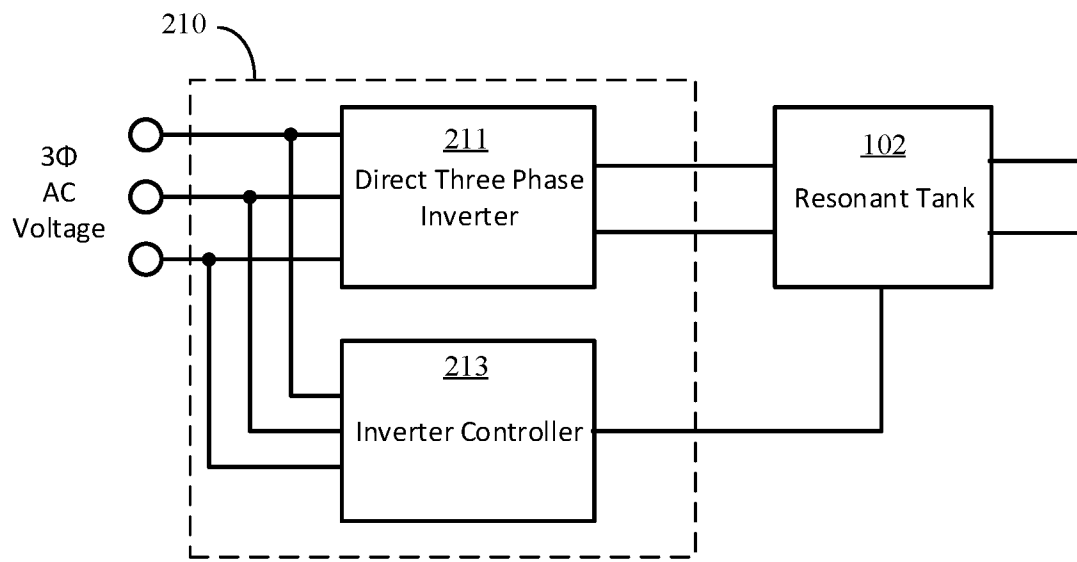


FIG. 2B

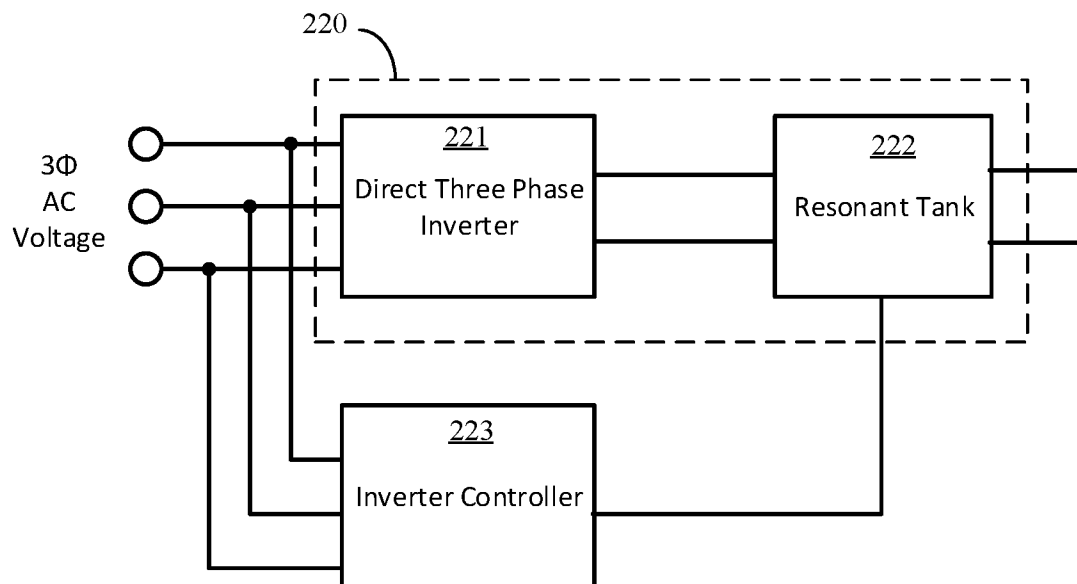


FIG. 2C

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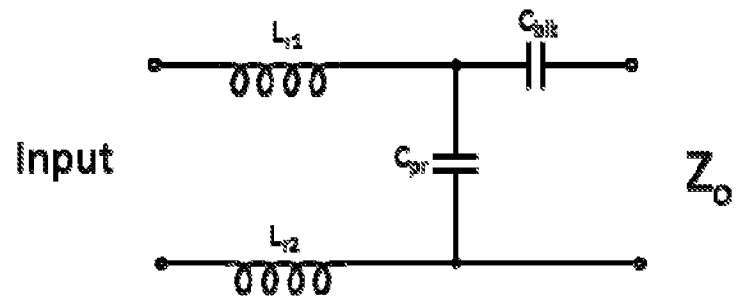


FIG. 3A

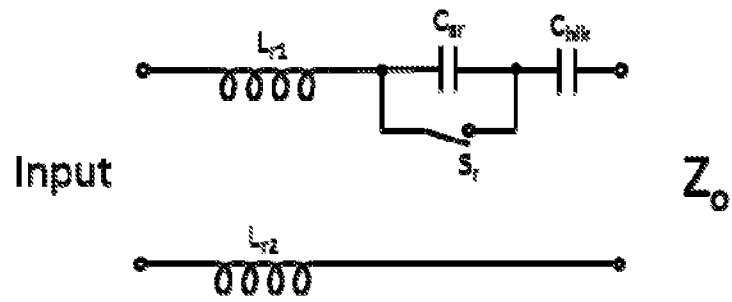


FIG. 3B

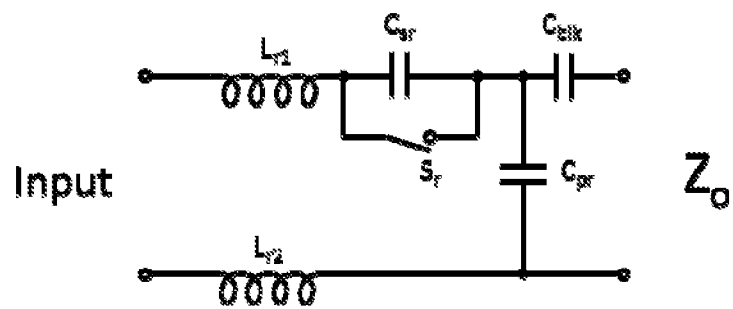


FIG. 3C

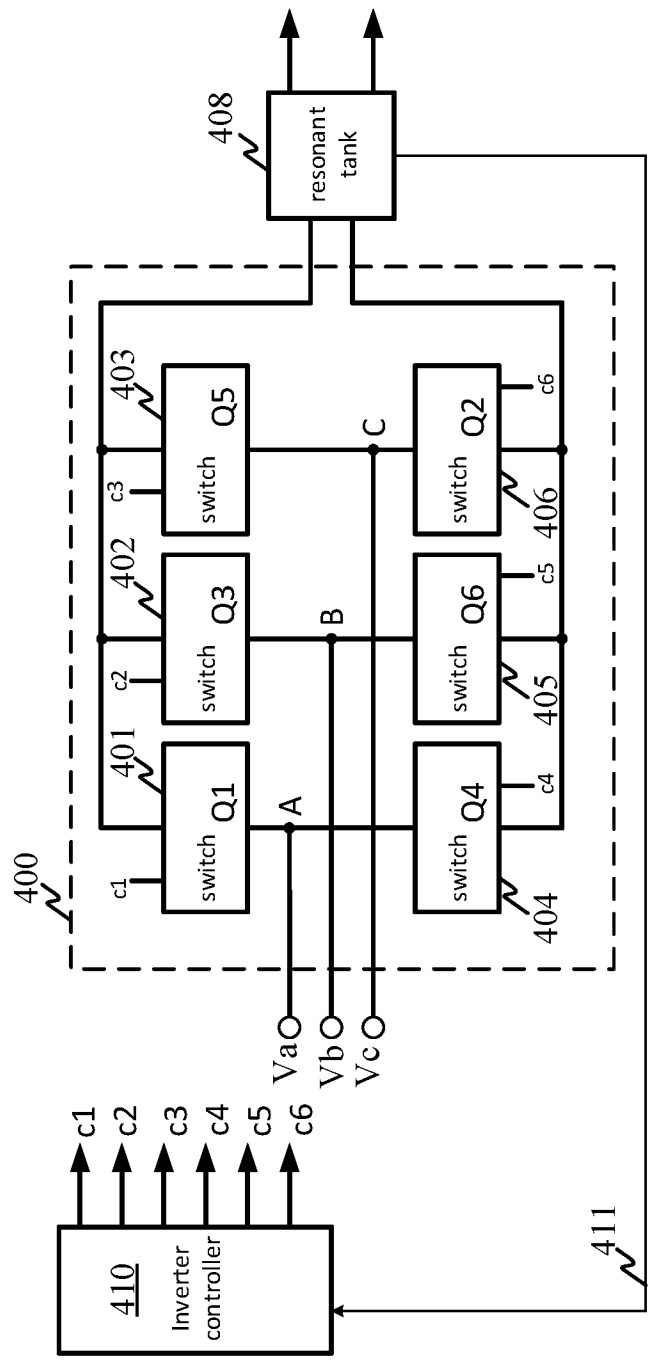


FIG. 4A

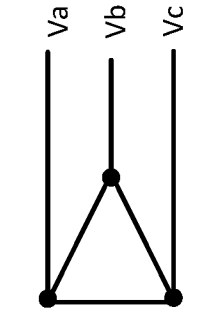


FIG. 4B

FIG. 4C

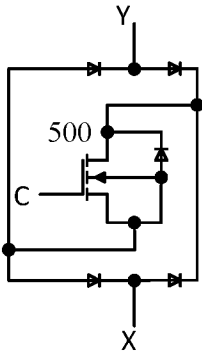


FIG. 5A

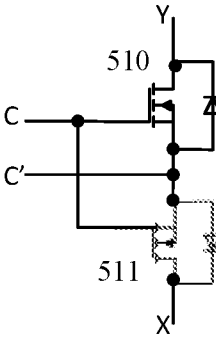


FIG. 5B

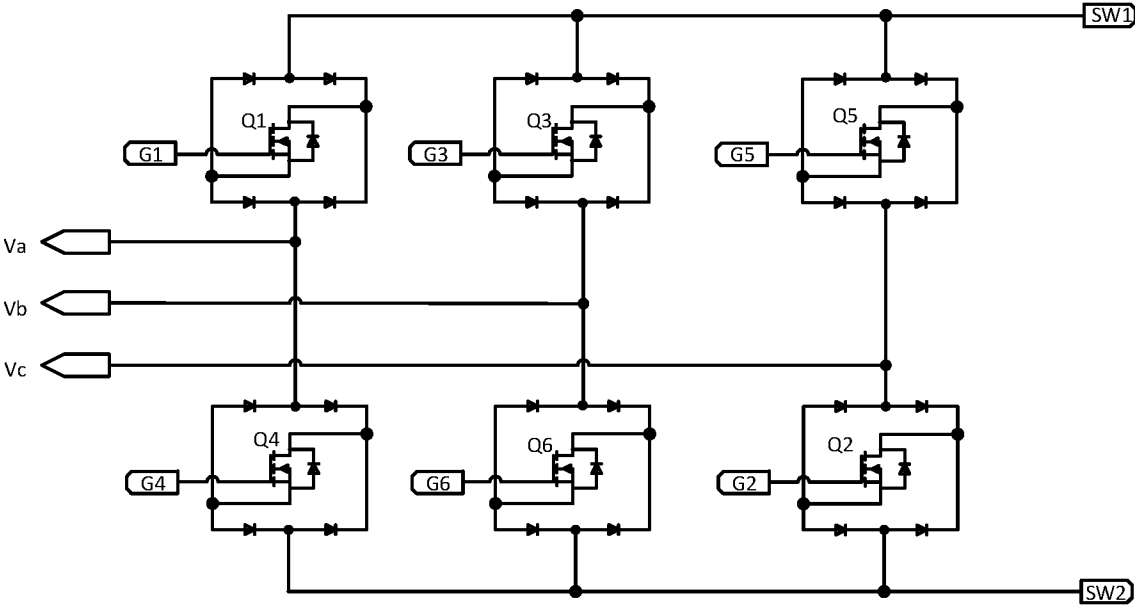


FIG. 6

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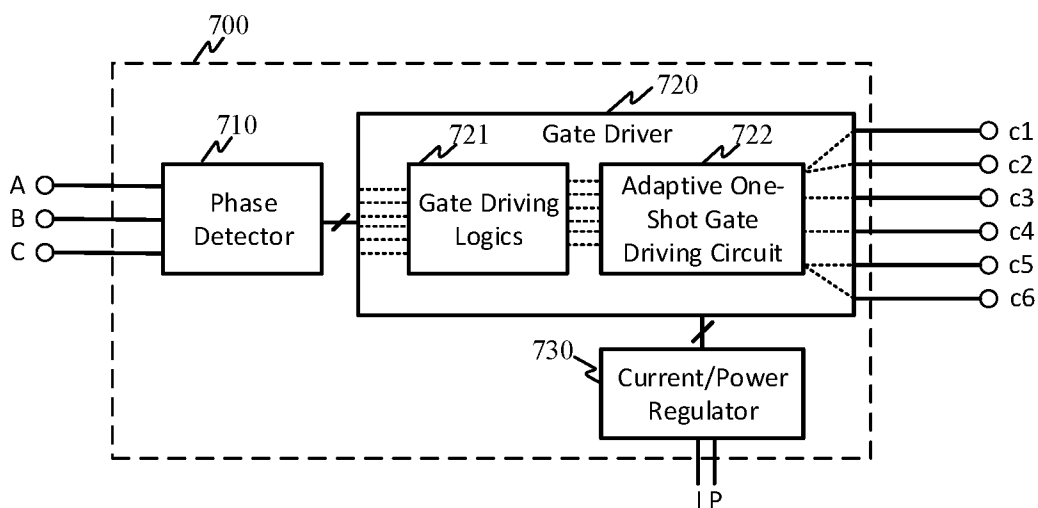


FIG. 7

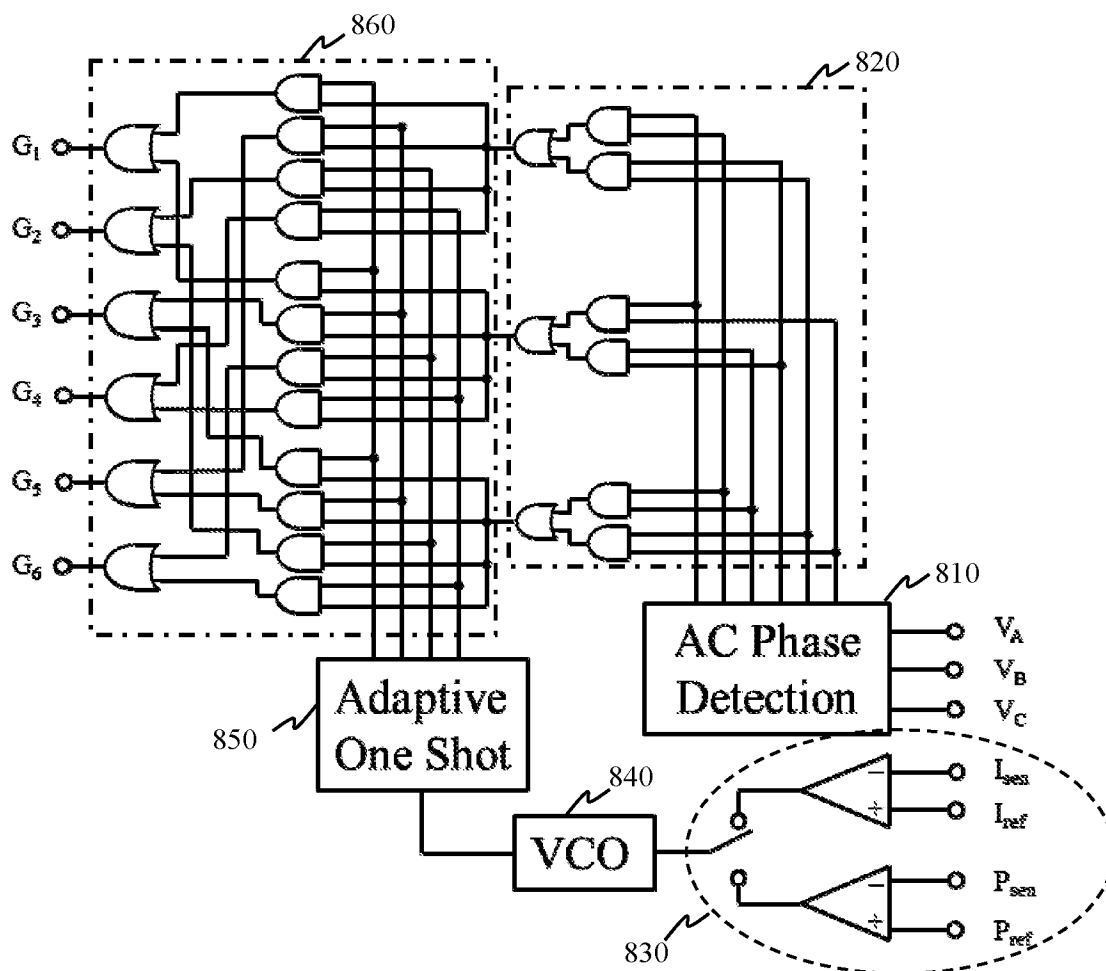


FIG. 8

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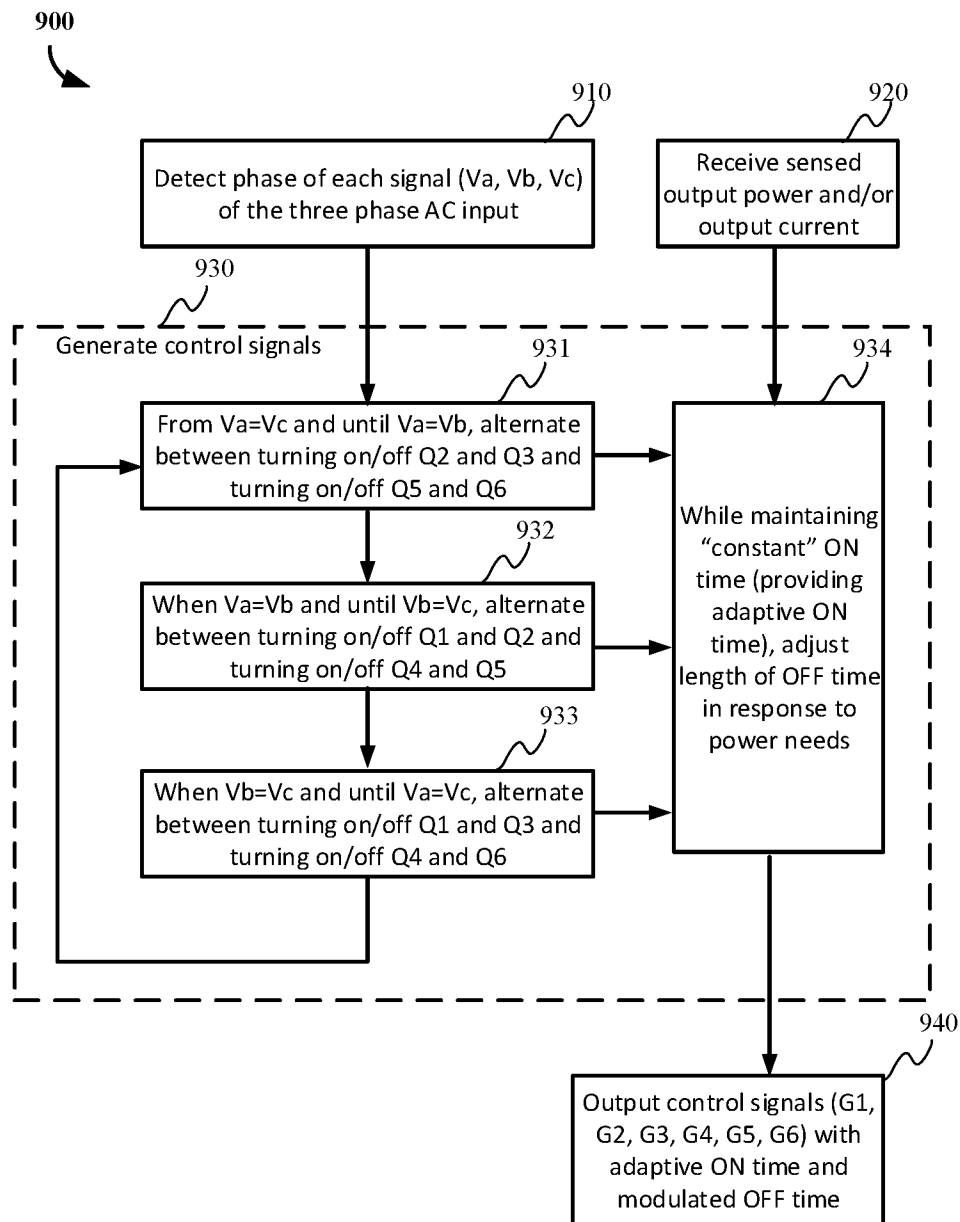


FIG. 9

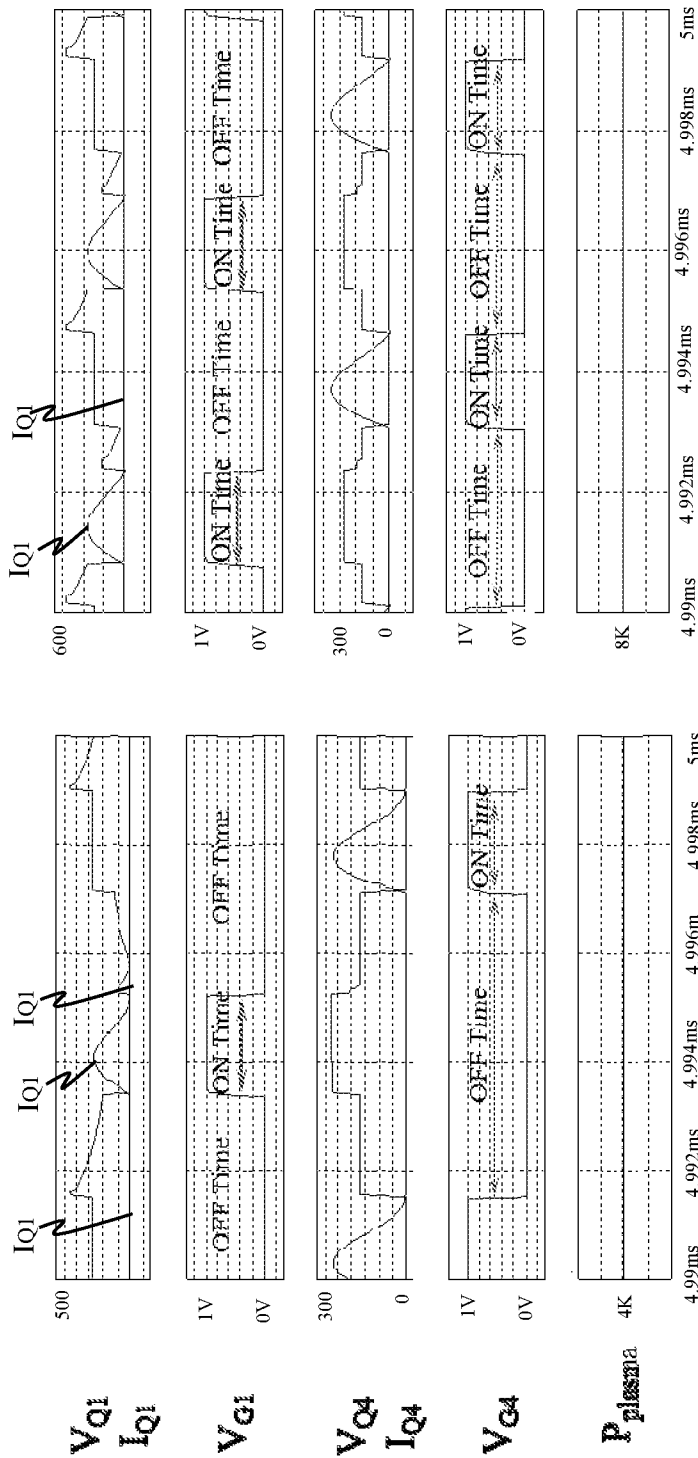


FIG. 10A

FIG. 10B

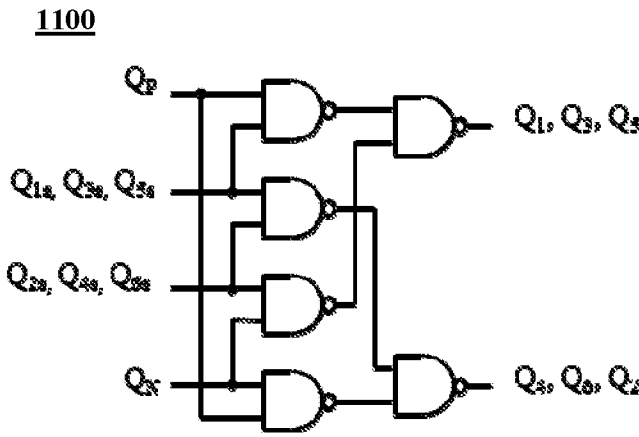


FIG. 11A

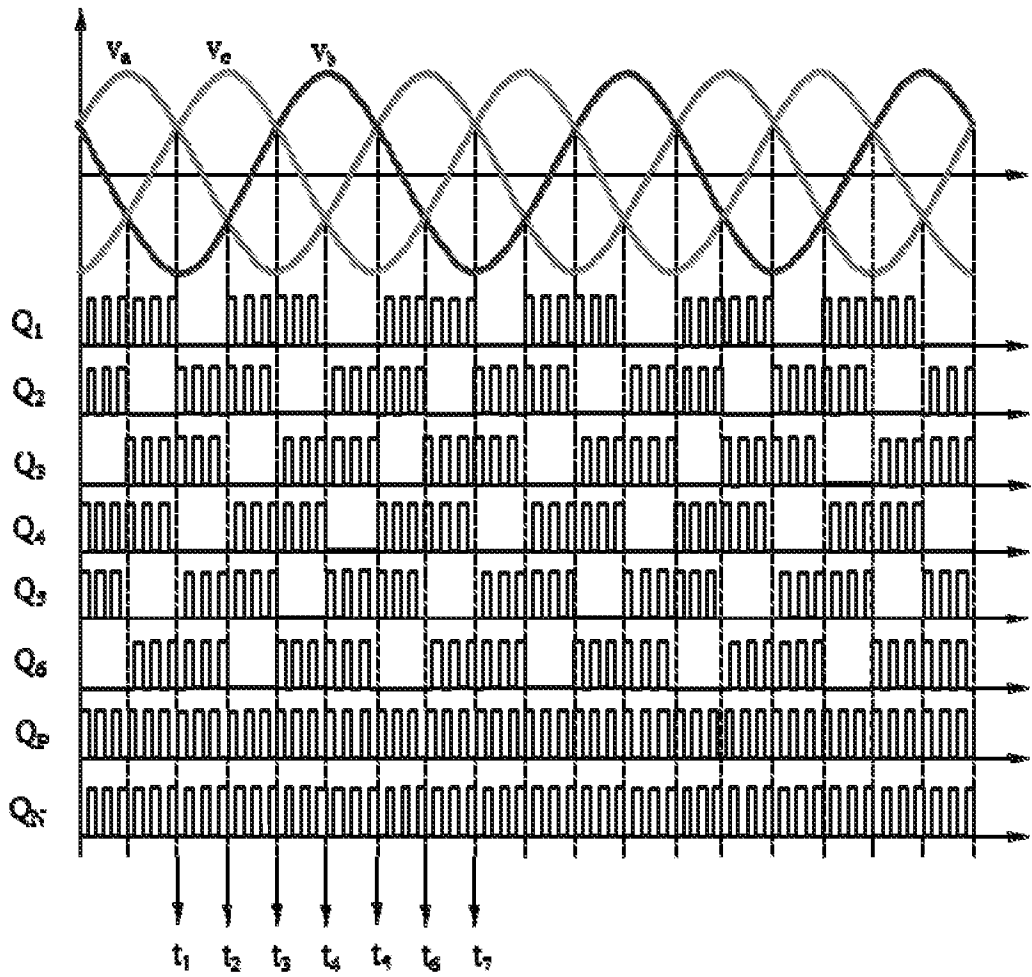


FIG. 11B

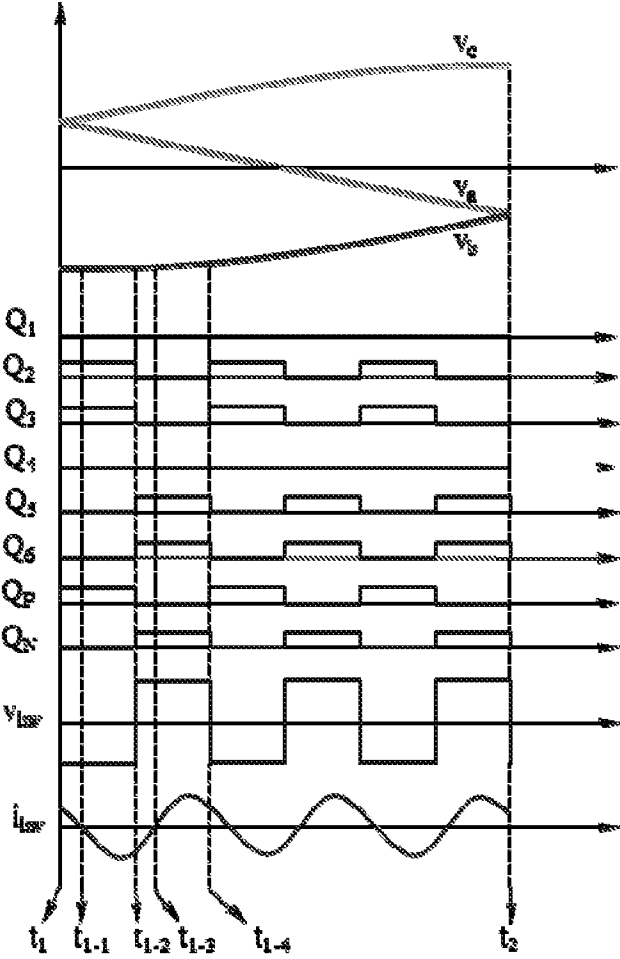


FIG. 12

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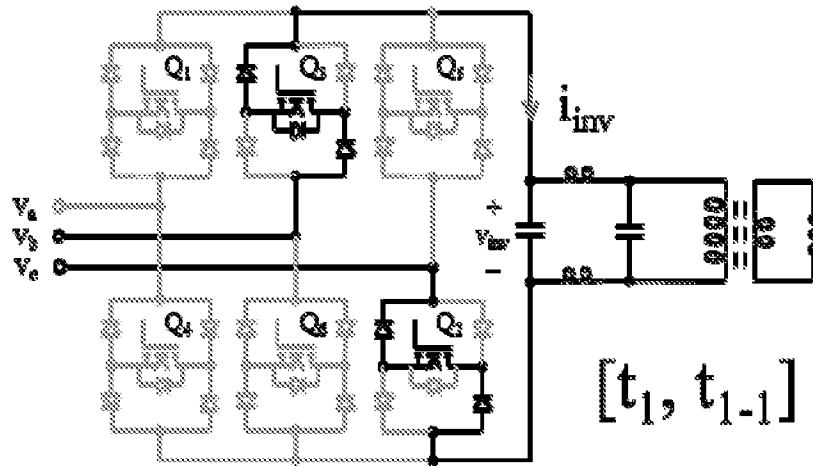


FIG. 13A

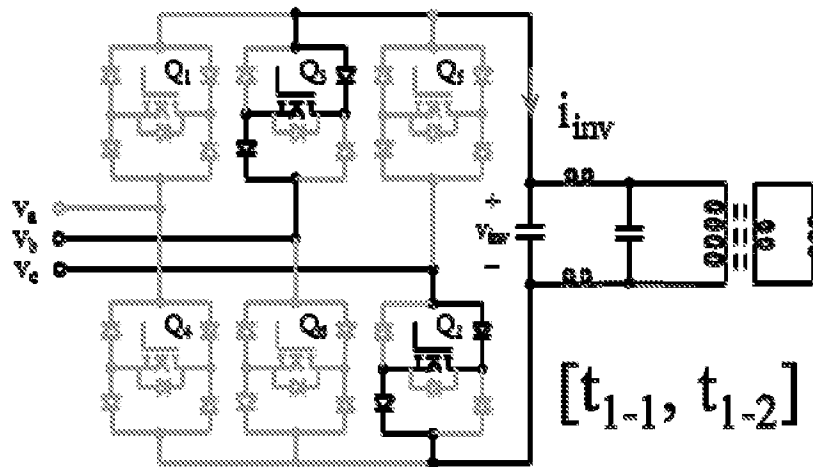


FIG. 13B

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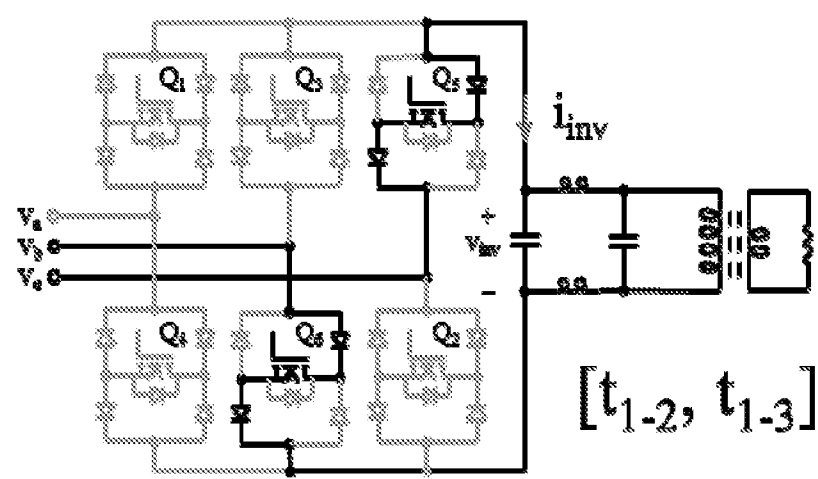


FIG. 13C

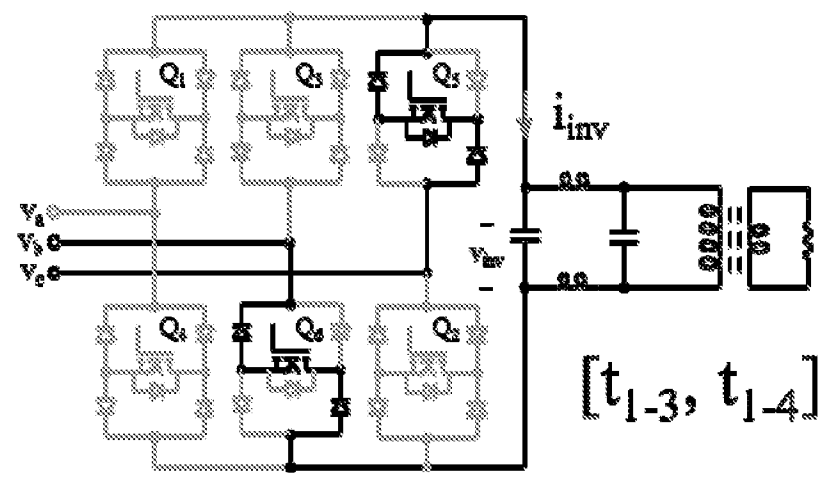


FIG. 13D

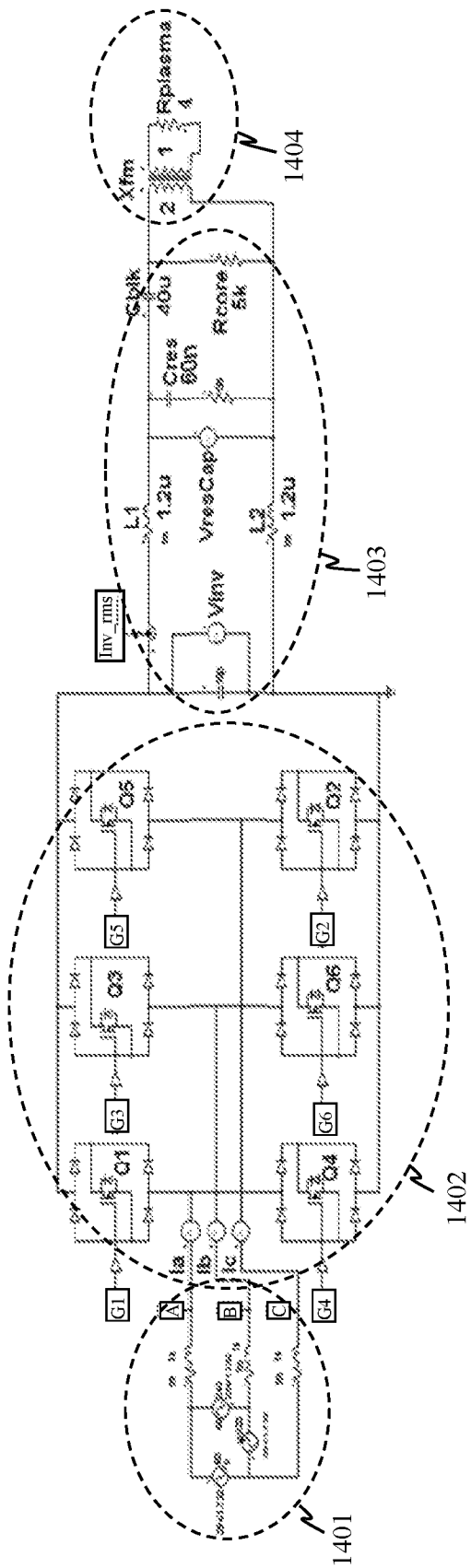


FIG. 14A

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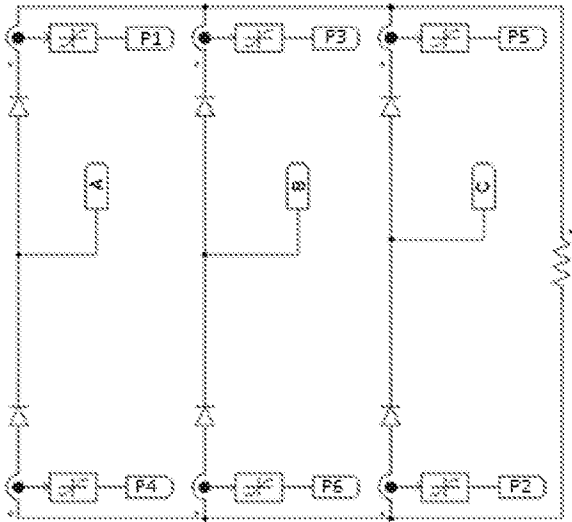


FIG. 14B

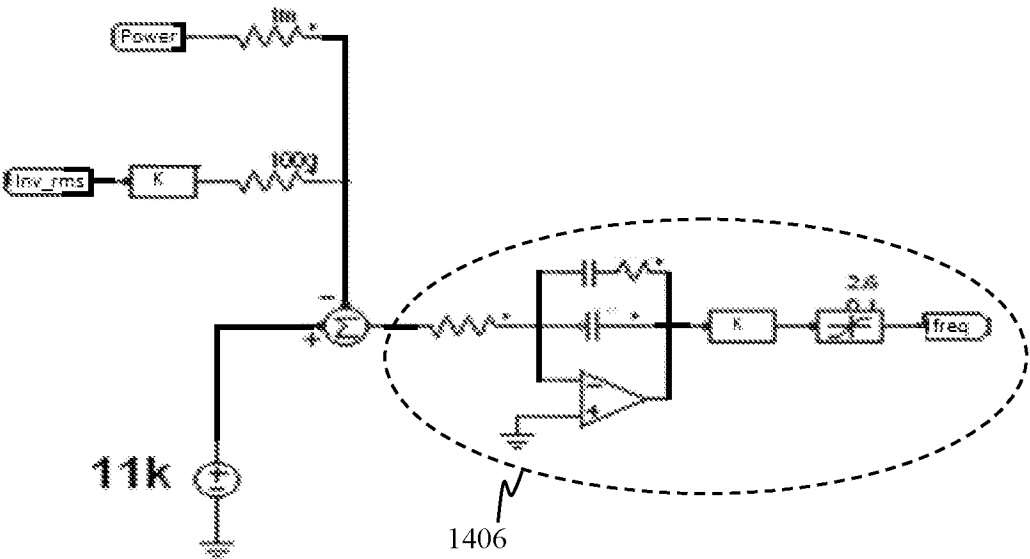


FIG. 14C

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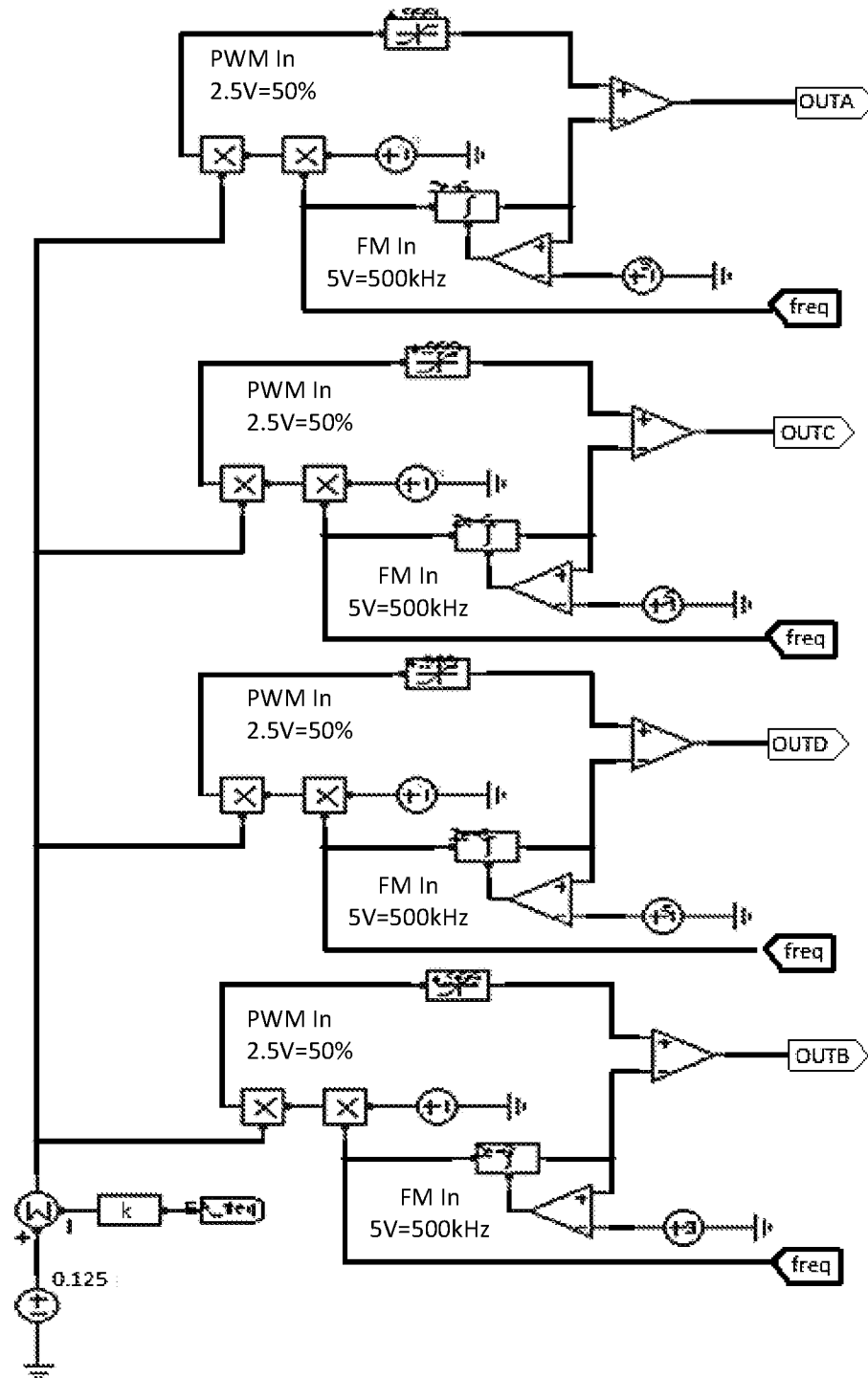


FIG. 14D

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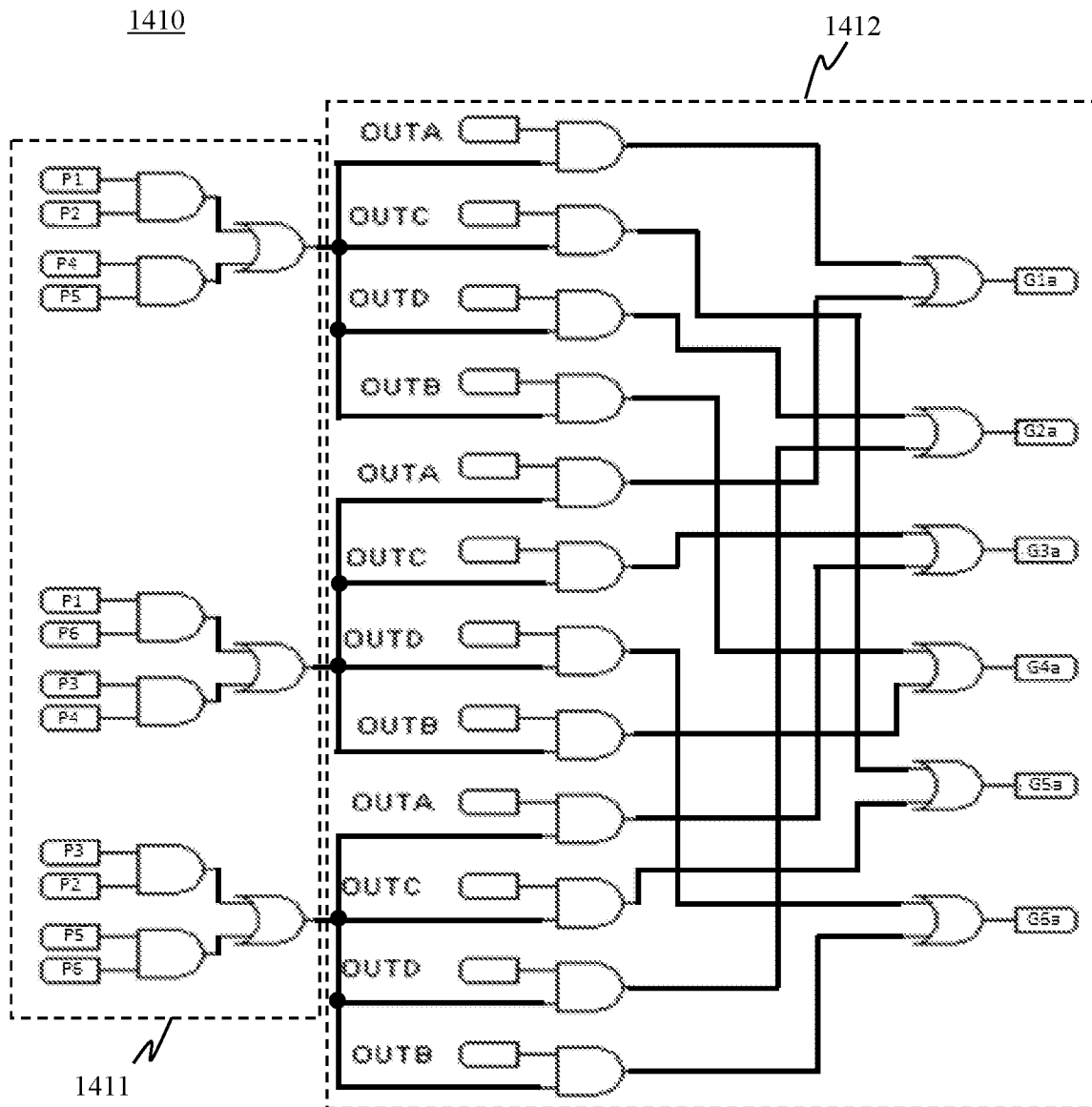


FIG. 14E

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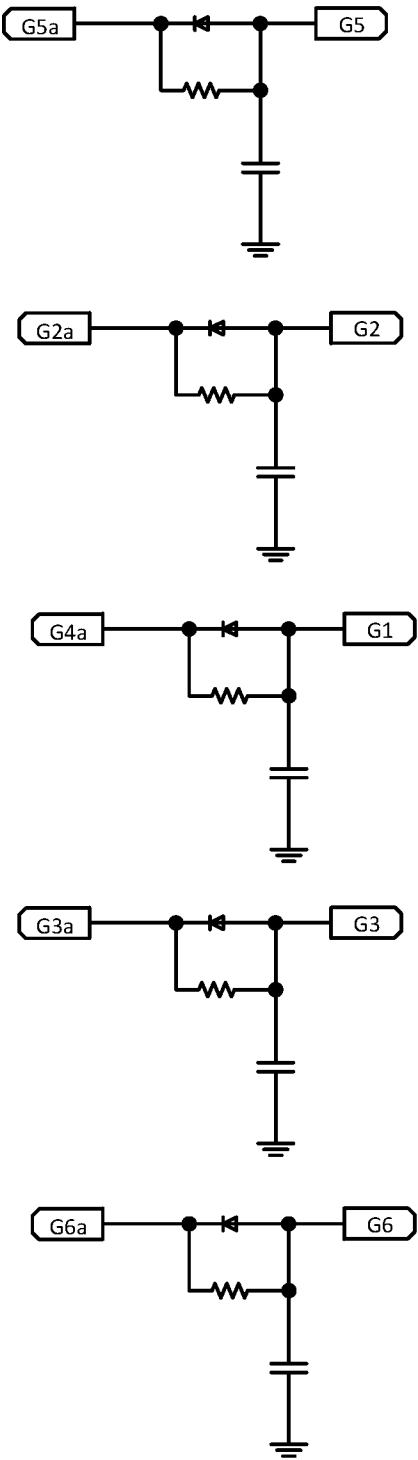


FIG. 14F

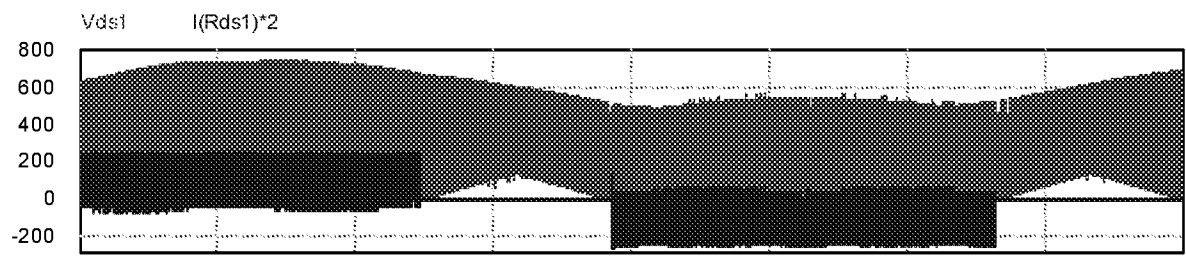


FIG. 15A

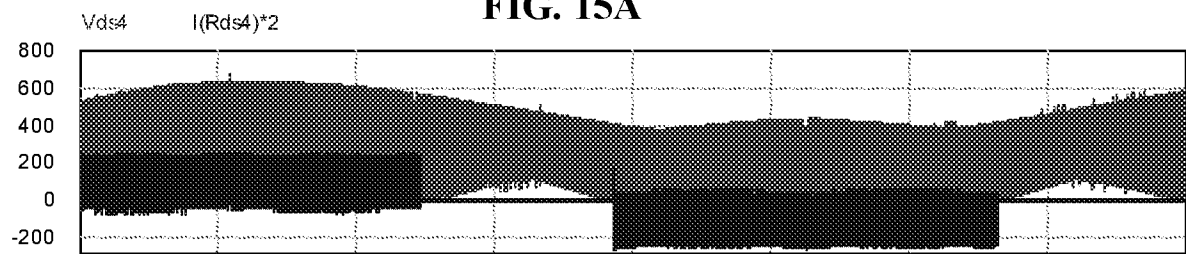


FIG. 15B

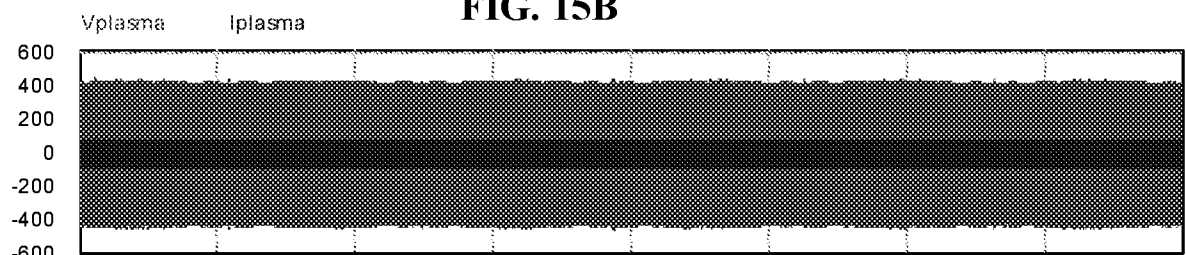


FIG. 15C

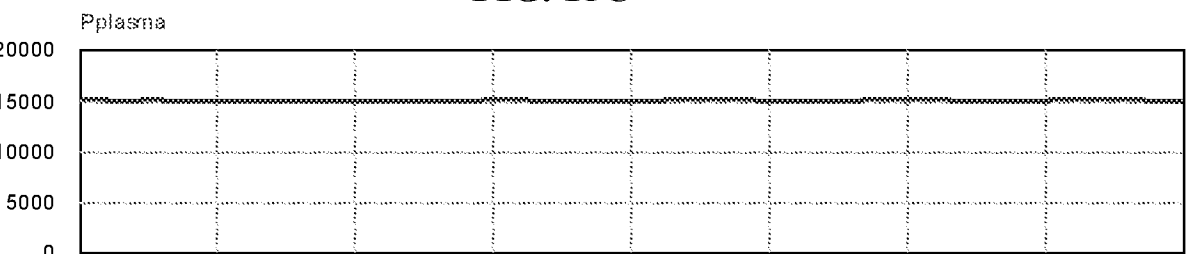


FIG. 15D

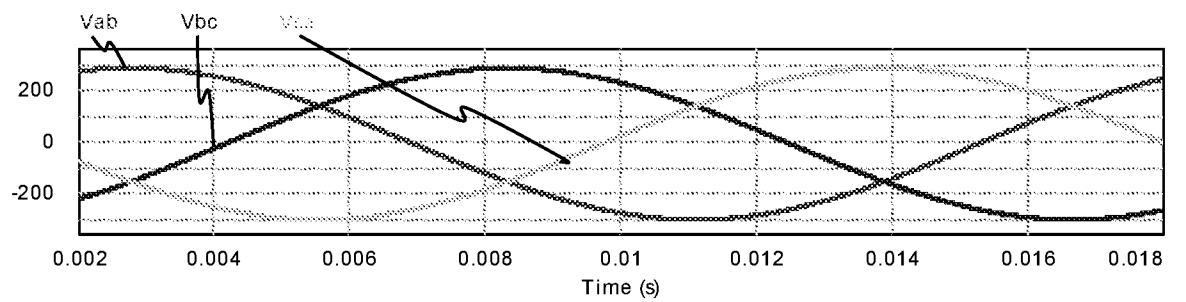


FIG. 15E

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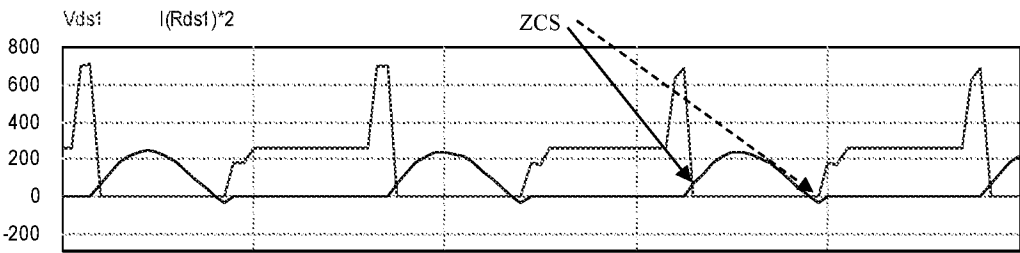


FIG. 15F

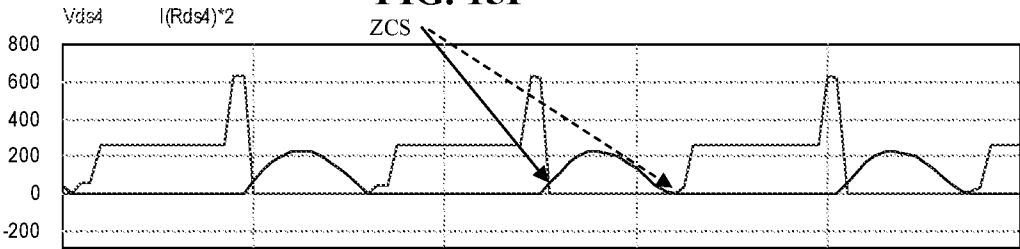


FIG. 15G

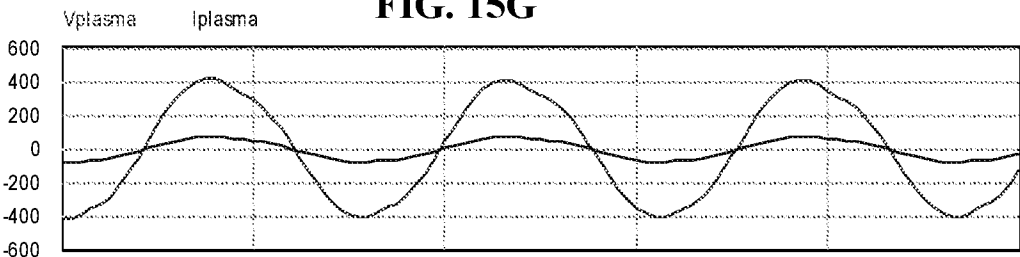


FIG. 15H

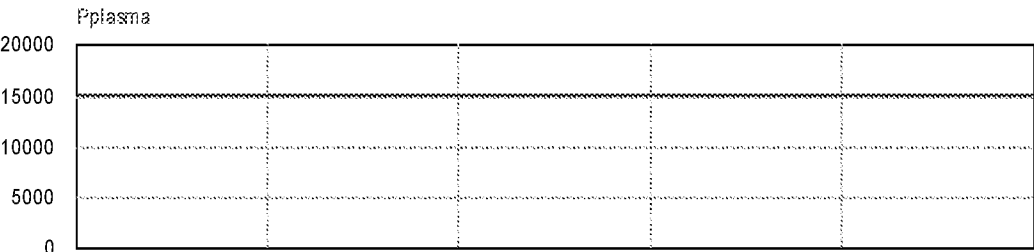


FIG. 15I

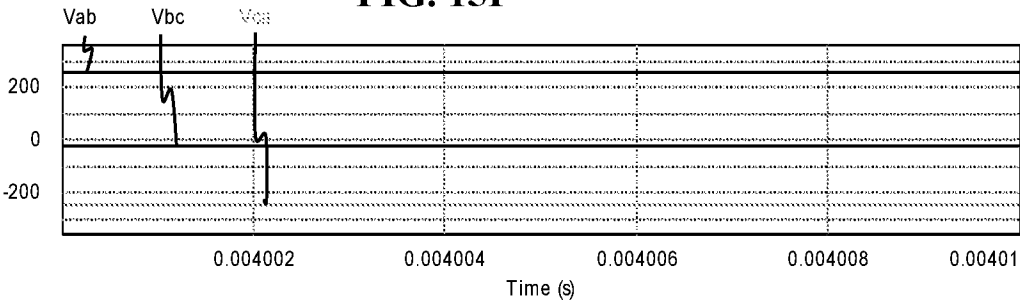


FIG. 15J



FIG. 15K

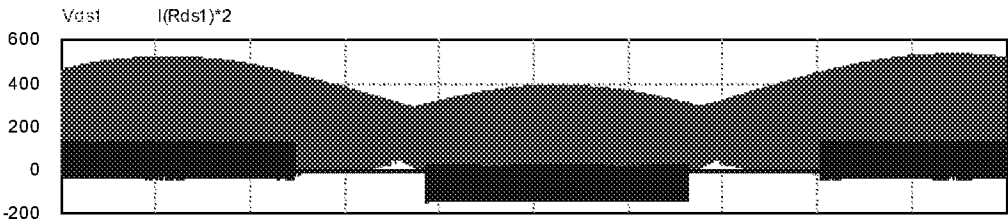


FIG. 16A

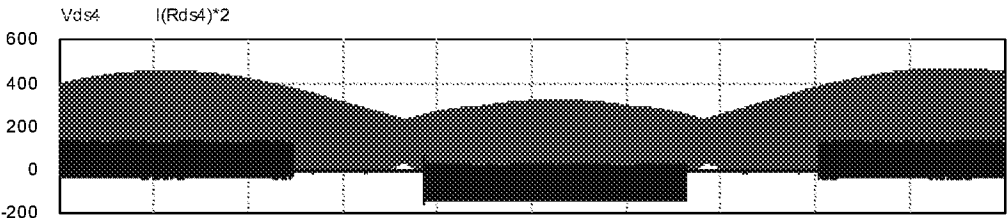


FIG. 16B

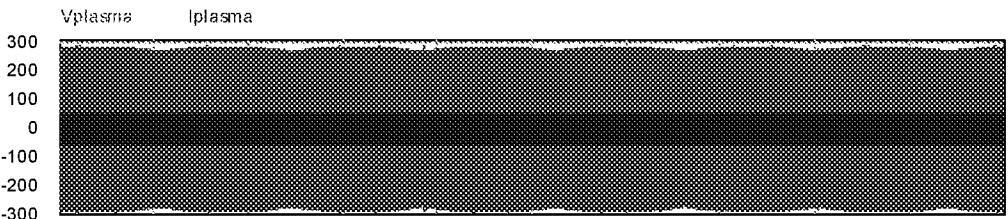


FIG. 16C

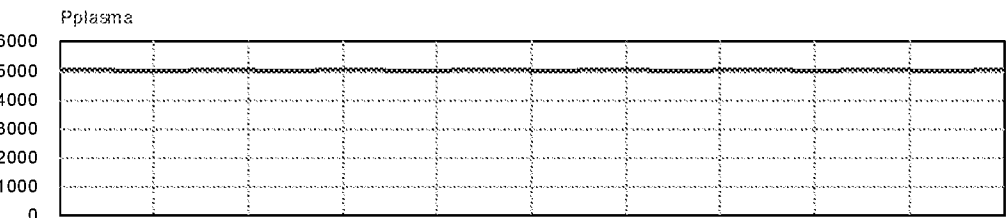


FIG. 16D

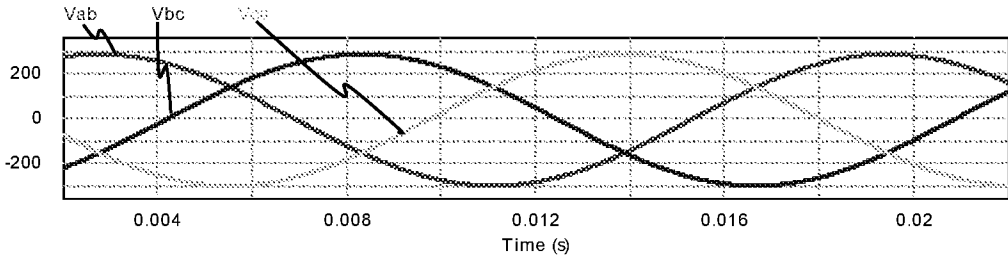


FIG. 16E

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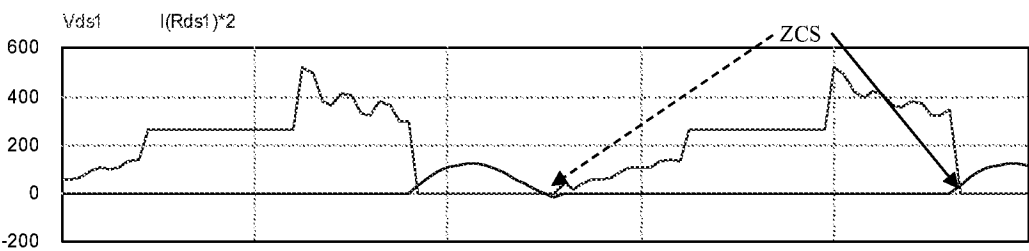


FIG. 16F

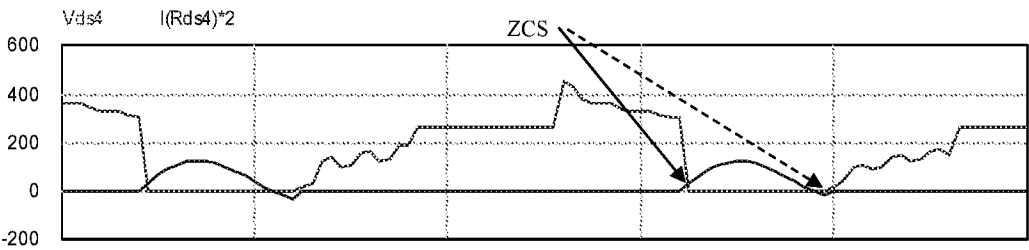


FIG. 16G

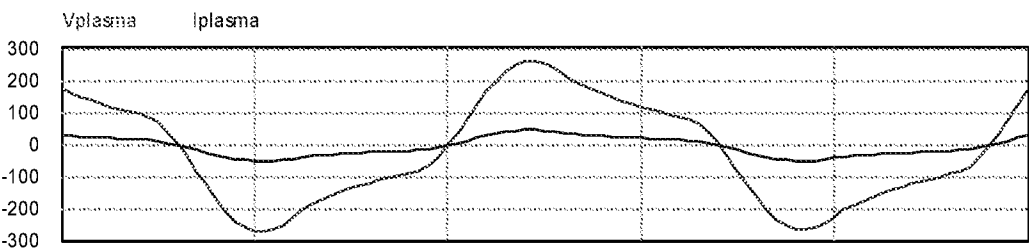


FIG. 16H

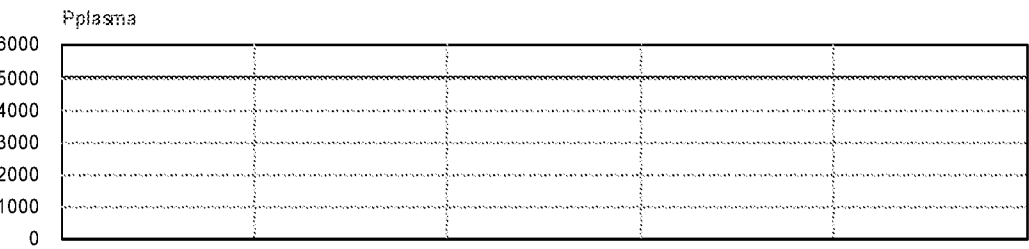


FIG. 16I

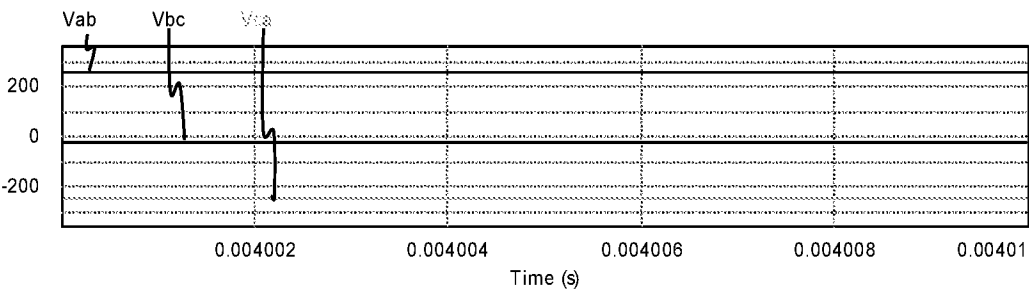


FIG. 16J

11kW Plasma Load: (Ton=1.43usec, Toff=2.39usec)

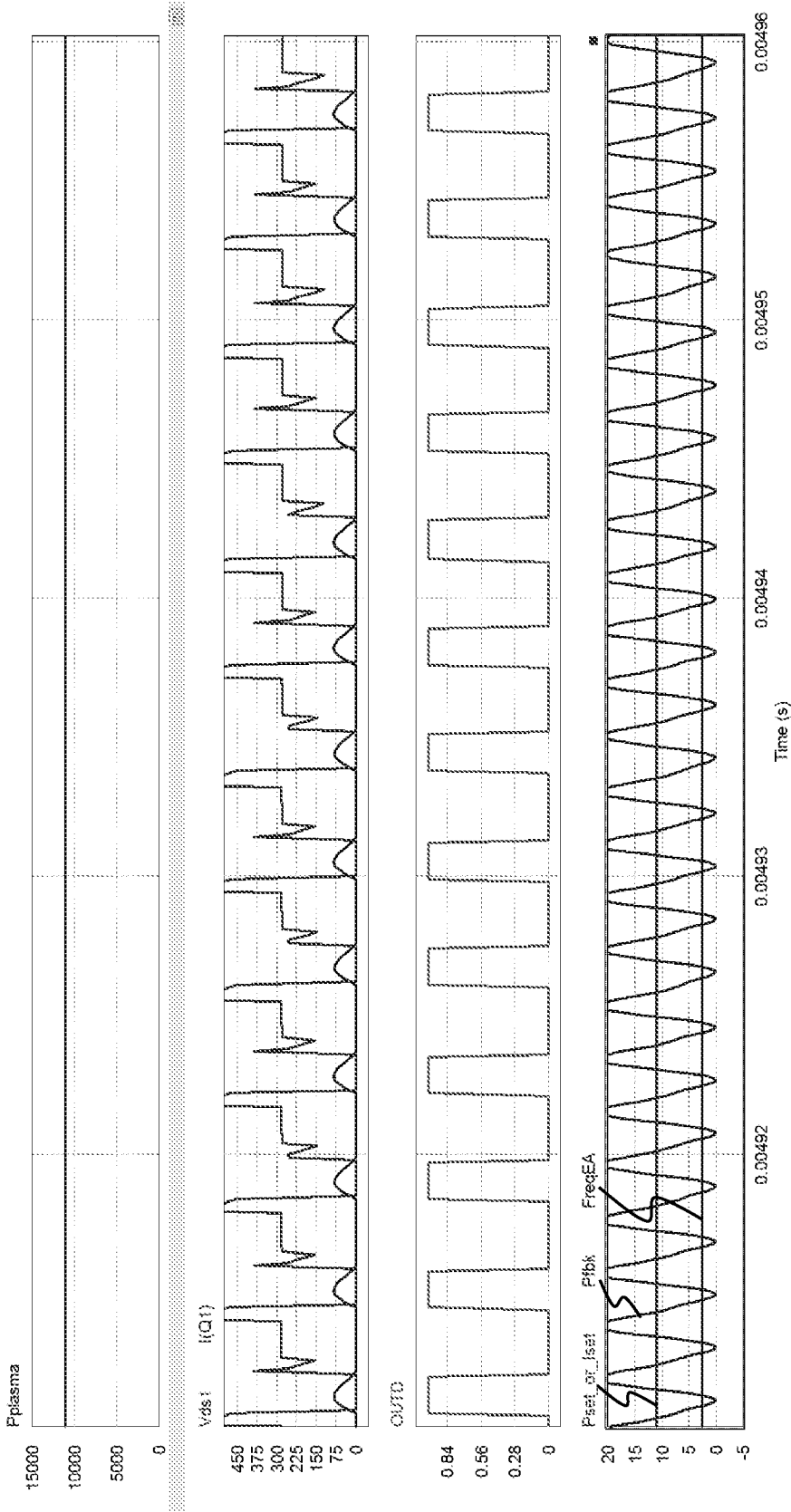


FIG. 16K

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2016/049017

A. CLASSIFICATION OF SUBJECT MATTER		
INV.	H01J37/32 H02M5/293	H02M5/22 H02M5/297
	H02M5/257	H02M5/27 H02M5/275
ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols) H01J H02M		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data, COMPENDEX, IBM-TDB		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2015/118990 A1 (UNIV HOKKAIDO NAT UNIV CORP [JP]; OMRON TATEISI ELECTRONICS CO [JP]) 13 August 2015 (2015-08-13)	1-9, 11-17,19
A	abstract; figures 1,2,3 paragraphs [0001], [0018] - [0029]	10, 20-23,25
A	US 2013/257311 A1 (TRAN KEN [US] ET AL) 3 October 2013 (2013-10-03)	1,2,4,6, 8,16,17, 19-23
	abstract; figures 1,2,4,6 paragraphs [0001], [0002], [0024] - [0030], [0034], [0038] - [0043], [0061]	
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A	abstract; figures 1-3 paragraphs [0001], [0064] - [0071]	1,3-6, 16,19, 20,22
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☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 25 November 2016		Date of mailing of the international search report 05/12/2016
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Remy, Jérôme

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2016/049017

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	CA 1 051 975 A (GEN ELECTRIC) 3 April 1979 (1979-04-03) abstract; figures 1-3 page 1, lines 1-8 page 4, line 17 - page 8, line 5 page 15, line 14 - page 17, line 5 -----	1,8 2,6,7, 16,19-22
X A	US 3 560 835 A (RETTIG CHARLES E) 2 February 1971 (1971-02-02) abstract; figures 1,2 the whole document -----	1,8 6,9,16, 19-22
X A	US 2003/095424 A1 (OATES DONALD COLIN MURRAY [GB]) 22 May 2003 (2003-05-22) abstract; figure 2 paragraphs [0001], [0070] - [0077] -----	1 6,8,12, 16,19-22
A	EP 0 603 683 A2 (KONE OY [FI]) 29 June 1994 (1994-06-29) abstract; figures 1,2,7 page 2, lines 1-3,50 - page 3, line 20 page 4, lines 38-56 page 5, lines 7-44 -----	1,2,6-9, 11-13, 16,19-22

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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